School of Land and Food

Impacts of Climate Change on the Potato (*Solanum Tuberosum* L.) Productivity in Tasmania, Australia and Kenya

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Masters of Agriculture (Agronomy),

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Declaration of Originality

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Declaration of co-authorship

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Thesis Publications

International Conference/ presentation

“Modelling Future Potato (*Solanum tuberosum* L) Production in Tasmania and Kenya” oral presentation at the International Horticultural Congress (IHC), Brisbane, Australia, August 2014.

Reports and popular literature

Predicting potato production in Tasmania and Kenya, article in Potatoes Australia Magazine, February/March 2015 Issue.

Thesis Abstract

This study assessed the potential impact of climate change on potato production both in Australia (Tasmania) and Kenya. Potato is an important commodity in both regions but there is little information about how this crop will respond to projected changes in climate compared to other regions. Previous to this doctoral study, APSIM-potato had only been tested and calibrated with a small number of datasets from a long-term experiment conducted in Lincoln, New Zealand with 'Russet Burbank' and its application to productivity modelling required further parameterisation and evaluation. A first step in this study was therefore to parameterise and evaluate the Agricultural Production System sIMulator (APSIM-potato) model under both Tasmanian and Kenyan potato growing conditions. Throughout this thesis the word parameterisation refers to the process of determining a set of parameter values deemed suitable for model use in a specific study area, and evaluation as the process of assessing the level of precision and accuracy of a model in reproducing observed data using performance measures and statistical values.

Four on-farm monitoring plots located on different farms were established in North-West Tasmania within well–managed potato fields grown during the 2012/13 cropping season. 'Russet Burbank' cultivar was planted at two sites and 'Moonlight' at the other two sites. In Kenya, experiments were conducted at Kabete, Kiambu County during the short rains (SR2013) and in the long rains (LR2014). The design for the SR2013 experiment was a split-plot with two water levels (supplementary irrigation and rain-fed) as the main plot factor and three genotypes as the sub-plot factor, with four replications. A randomized complete block design was used in the LR2014 experiment, with three nitrogen levels (23, 63 and 104 kg N/ha, hereafter referred to as N23, N63 and N104 treatment levels) and four replicates. Measured soil, weather and crop datasets for 'Russet Burbank' and 'Moonlight' in Tasmania,

and for ‘Unica’, CIP 300046.22 and ‘Shangi’ in Kenya were used to parameterise and evaluate the model.

In both Tasmania and Kenya, the model adequately captured the phenology and the partitioning of assimilates to the tuber state variable over time, with a good index of agreement using a Normalized Root Mean Squared Error (N-RMSE) and Modelling Efficiency (EF). In Tasmania, measured mean Tuber Dry Matter (TDM) was 17 t ha^{-1} for ‘Russet Burbank’ compared to a simulated value of 20 t ha^{-1}. N-RMSE values between observed and simulated TDM ranged between 10 to 20%, with a mean of 16.3% for ‘Russet Burbank and 14.5% for ‘Moonlight’, and a mean EF of 1.0 for both cultivars. For ‘Moonlight’ the mean simulated TDM value was 16.0 t ha^{-1} compared to the measured value of 15.1 t ha^{-1}. Similarly, prediction of phenology and tuber N-uptake was good: respectively a mean N-RMSE value of 25.7% and 20.9% for ‘Russet Burbank’, 24.2% and 32.7% for ‘Moonlight’. However, prediction of other parameters (leaf and stem dry biomass and LAI) were poor with N-RMSE values ranging from 27.6 to 40.8% for ‘Russet Burbank’, and 20.7 to 48.2% for ‘Moonlight’.

In Kenya, the model predicted TDM yield with good precision, providing a mean N-RMSE of 18.4% for SR2013 and 28.7% for LR2014, and a mean EF of 0.9 for both seasons. Similarly, prediction of phenology was good, the model providing a mean N-RMSE value of 20.8% and an EF value of 0.8 for both SR2013 and LR2014. In the SR2013 experiment, the measured TDM across the three cultivars under rain-fed conditions was 3.8 ±0.2 t ha^{-1} compared to simulated value of 4.4 t ha^{-1}. With supplementary irrigation, the observed value was 6.2 ±0.2 t ha^{-1}, close to the simulated value of 6.3 t ha^{-1}. In the LR2014 experiment, when pooled across nitrogen levels, the model underestimated TDM, providing a mean simulated TDM at 6.6 t ha^{-1} against the measured value of 7.7 ±0.4 t ha^{-1}. In contrast, the index of agreement between simulated and observed aboveground biomass was generally low (a mean

N-RMSE value of 37.2% in the LR2014 experiment and 47.5% in the SR2013 experiment, EF values ranging from -0.3 to 0.3 in the SR2013 and -0.5 to 0.4 for the long rains).

The simulation results provide a database for further testing of the model and this work provides future users with a foundation to further improve the model. While the model accurately predicts plant phenology and TDM, modification of other key crop specific parameters are still needed to improve its accuracy when simulating the development of other plant organs. Further refinement of the model will require collection of long-term field crop data.

The model's ability to realistically simulate potato phenology and TDM provided a sound basis to investigate the potential impacts of climate change on potato productivity with confidence. The calibrated APSIM-potato model was used to quantify the potential impact of future climate scenarios on potato productivity in the two contrasting environments of Tasmania and Kenya. Data used in the model to simulate future climates included dynamically downscaled bias-corrected climate projections for Tasmania (Climate Futures Tasmania), and an ensemble of climate projections under the CORDEX–Africa initiative for Kenya.

Across the three potato growing sites studied temperature projections indicate a 1.2 °C increase at each site for maximum temperature and 1.3 °C for minimum temperature by 2050. By 2085, a 2.4 °C increase is projected for maximum temperature and for minimum temperature; a 2.6 °C increase is projected. Annual rainfall is projected to increase across the study sites relative to the baseline period by 6.1%, 4.5%, and 9.0% at Cressy, Forthside and Scottsdale respectively by 2085. Similarly, the coefficient of variation (CV) of annual and seasonal rainfall is projected to increase by 2% at both Scottsdale and Forthside above the baseline value of 13% and 14% respectively and by 3% at Cressy above the baseline value of

14%. Annual and seasonal rainfall intensity is projected to increase from the baseline to 2085.

Whilst temperature is projected to increase in the Tasmanian potato growing regions, the duration at which the crop is exposed to temperatures outside the crops optimal range is negligible. Consequently, climate change will have little influence on projected future multi-model ensemble median (MME) tuber yield under current farmer practice (based on the last five years 2012 to 2016). There is a steady increase in the rate of growing degree day (GDD) accumulation from planting to harvest; 4.8% by 2050 and 12.3% by 2085 relative to the baseline period of 1981-2010 across the three sites. This increased rate in GDD accumulation is projected to shorten the time to crop maturity against the baseline period by 10 days in 2050, and 15 days by 2085. Shortening of the duration to crop maturity could potentially translate to savings in irrigation and the amounts of pesticide used. However Tasmania is free of some of the major potato pests and diseases. This situation could change as shifts in climate encourage the establishment of pests and diseases or if strict biosecurity regulations are not maintained. Extreme events leading to waterlogging could destroy crops. Thus it is difficult to predict what a potential shortening of 10 - 15 days will imply for potato production in Tasmania.

In Kenya, marked inter-annual and inter-seasonal rainfall variability is projected for the two sites investigated, with no clear trend throughout the 21st century. Annual rainfall is projected to reduce at Bomet by 46.1% by 2050 and 42.3% by 2085 while the opposite is projected at Kabete with a 1.6% increase by 2050 and by 15.9% by 2085. In both sites, a reduction in annual rainfall is projected for LR and an increase is projected for SR. At Bomet rainfall intensity and number of rain days are projected to decrease and the opposite is projected at Kabete. Mean maximum and minimum temperature are projected to increase across the potato growing areas investigated. The projected increase is higher at Kabete, the lower altitude region with a mean increase of a 2.4 °C (Tmax) and 2.6 (Tmin) by mid-century and 4.1 °C (Tmax) and 4.4 °C (Tmin) increase by 2085 compared to 0.6 °C (Tmax) and 1.3 °C (Tmin) by mid-century and 2.3 °C (Tmax) and 3.1 °C (Tmin) in Bomet. In terms of generating future climatic data, refinement of the projected data and bias-adjustment is recommended for Kenya as there were large disagreements among the projected datasets generated by the different GCMs used in the study to generate future climate data for the two study sites.

The modelling predicted that Kabete will experience an increasing number of hot days (maximum daily temperature ≥ 24 °C but <34 °C) as the century progresses, thus future potato production may be less viable here than in Bomet where mean daily temperatures are within the ideal range throughout the century (mean of 17 °C, 18 °C and 19 °C for the baseline, 2050 and 2085 compared to 21 °C, 24 °C and 26 °C for Kabete). At Bomet, simulated potato yields were less variable than at Kabete though simulation results indicate an increase throughout the century in both sites.

As temperatures in Bomet are likely to be within the optimal range for potatoes tuber yield will most likely be driven by rainfall amount, and more importantly, distribution. In Kabete, where temperatures are predicted to be intermittently above the optimal range, temperature and rainfall are the key drivers in both determining and reducing potato tuber yield. Importantly, benefits of increasing CO_2 concentrations counteracted the negative impacts of elevated temperatures and contributed to the projected positive impacts of tuber yield in a warmer future climate particularly in Kabete.

The implication of this scenario is that potato farmers in Kenya, and particularly Kabete, must adopt heat resistant cultivars as the overall tuber yields are lower with a lot of seasonal variability compared to Bomet. Also, due to year-to-year variability in Kenyan rainfall, development of irrigation systems to optimise and stabilise tuber yield must be implemented. Simulation results shows that a poor year either in Bomet or Kabete is associated with low in-crop rainfall and high leaf water and leaf expansion stress levels unlike in Tasmania where intensive irrigation is practised, the crop always has ample supply of water.

This study has shown that APSIM-potato has good ability to simulate tuber dry matter yield and nitrogen uptake under the Tasmanian conditions and this justifies its use in potato modelling studies. Under suboptimal and water stress conditions as was the case in Kenya, APSIM-potato realistically reproduced observed TDM though to a lower precision compared to cultivars modelled in Tasmania. Nevertheless, the simulation was considered accurate good enough to provide confidence and the model was used to explore the possible impact of climate change on both Kenyan and Tasmanian cultivars.

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Abbreviations

ALB: Apical lateral branches

AMSL: Above mean sea level

ANOVA: Analysis of Variance

APSIM: Agricultural Production Systems sIMulator

BD: Bulk density

BLB: Basal lateral branches

CFT: Climate futures Tasmania

CIP: International Potato Center

CV: Coefficient of variation

DAP: Days After Planting

EF: Modelling efficiency

FAO: Food Agriculture Organization

GCM: Global circulation model

GDD: Growing degree days

ICPAC: IGAD climate prediction and application centre

IPCC: Intergovernmental Panel on Climate Change

ISAM Integrated science assessment model

KES: Kenya Shillings

LAI: Leaf Area Index

LBHT: Late blight heat resistant

LR: Long rains (Kenya)

LTVR: Lowland sub-tropics virus resistant

MME: Multi-model ensemble

MoA: Ministry of Agriculture (Kenya)

MS: Main stem

PLRV: Potato leaf roll virus

PVY: Potato virus Y

RCBD: Randomized complete block design

RCP: Reference concentration pathways

RMSE: Root mean square error

SN: Stem number

SR: Short rains (Kenya)

SREs: Special report on emissions scenarios

TDM: Tuber dry matter yield

TMax: Maximum temperature

TMin: Minimum temperature

TPS: True potato seed

TVRF: Tasmanian Institute of Agriculture Vegetable Research Facility

Chapter 1 : General Introduction

Why this research topic?

The concept of my research began in November 2010, when a potato farmer in the high altitude areas of Marakwet West sub-county in Kenya mentioned that global warming and higher temperatures meant she could now plant maize. As a potato researcher, I wondered about the future of potatoes in Kenya; what are the potential impacts of a warmer future climate on potato productivity? Will potato farmers at low latitudes no longer be able to grow potatoes? Will farmers at higher altitudes shift to growing maize because potatoes become susceptible to pests and diseases under warmer conditions? How can we predict the impact of climate change on potato productivity? Can potato farmers effectively adapt to any impact of climate change? These are the type of questions that formed the basis for the research presented in this thesis.

Why potato is important

Worldwide, the potato (*Solanum tuberosum* L), also known as the "humble tuber" is currently grown in 149 countries and consumed daily by more than a billion people, making it the world's most important tuber and non-grain crop (Birch et al. 2012; FAO 2015). *Solanum tuberosum* is cultivated in all the continents except Antarctica and in nearly all the global climates from latitudes of 65 °N to 50 °S and from altitudes ranging from sea level to 4,000 m (Haverkort 1990; Midmore 1992; Birch et al. 2012). The main factor explaining its adaptability is its wide range of optimal temperature under long day length conditions (Haverkort & Kooman 1997). Cultivated potato (*Solanum tuberosum*) is a tetraploid (2n = 4x

= 48) with tetrasomic inheritance and highly heterozygous (Carputo & Frusciante 2011). Due to this adaptable nature, potatoes are now grown in nearly all global agricultural climates and altitudes.

Globally, potatoes are among the top 10 highest food commodities produced annually and among the 50 food commodities by tonnage that contribute to the top 90% of calories, protein, fat and weight (Khoury et al. 2014; FAO 2015). Approximately half of the total global production of potatoes is consumed fresh. The other half is processed into food (frozen, dehydrated and starch) or is used for non-food products such as industrial starch, alcohol and seed. Nearly 10% of global production is used as seed (FAO 2015). Considering the massive quantity of potatoes produced worldwide, e.g. an average of 322 million tons annually for the period 1993 to 2013 (FAO 2015), and the proportion of this production that is consumed as a fresh source of nutrition, the role potatoes play in assuring global food security is critical.

Compared to major grains such as rice, wheat and maize, the potato has several advantages; it has a high harvest index, a short cropping cycle and a large per-area and per-time production (FAO 2008; Lutaladio & Castaldi 2009; Birch et al. 2012; Haverkort & Struik 2015). Under optimum conditions, potato can produce over 40 t ha^{-1} of fresh tubers within a period of 120 days (FAO 2008). Potato has a higher "crop per drop" or the water use efficiency (WUE, gram of potato produced per litre of water used) producing more dietary energy per unit of water; 5,600 kcal per litre of water thereby meeting the daily needs for a person with less than a litre of water (Birch et al. 2012).

Potato is a major vegetable crop in Australia

Potatoes are cultivated in all states of Australia. South Australia, Tasmania, and Victoria are the leading potato producing States. Together, the three States contribute over 70% of the national total production (ABS 2014). In terms of volume and value, the potato is by far the leading vegetable produced in Australia, representing about 40% of the total volume and 19% of the value during a ten-year period from 2002-03 to 2011-12 (ABS 2014). Approximately 1.3 million tons of potatoes worth about 0.7 billion dollars was produced in 2011-12(ABS 2014).

In Tasmania, the Island State of Australia, potato is the mainstay of the vegetable industry. In 2012-13, it represented about 70% of the vegetable industry volume (ABS 2014; AUSVEG 2014). In 2009, a wide range of vegetables worth $239 million was produced, with potatoes accounting for 41% of the value (ABS 2014). Over 80 percent of the potatoes produced in Tasmania are sold to the other states and the remainder is consumed locally (DPIPWE 2014).

Potato is a staple food crop in Kenya

In Kenya, potato is the second most important food crop after maize, with approximately 800,000 growers, millions of rural and urban traders and consumers, and an estimated annual farm gate value of Kenya shillings (KES) 13 billion (USD 150 million) (Kaguongo et al. 2013). Over 85% of the potatoes produced in Kenya are consumed fresh as boiled, fried, mashed or in stews. Processing is limited to the production of French fries and crisps. Rapid population growth, urbanization, change of food preference and expanding middle class consumers continue to create demand for potatoes (Kaguongo et al. 2013).

Potato production systems in Australia and in Kenya

In Australia, potatoes are cultivated, processed and value-added in a highly efficient, competitive and globalised sector of the food industry. The industry is characterised by a highly skilled personnel throughout the value chain and secured market access backed up with world – class technologies and phytosanitary measures (DPIPWE 2014). Because of its geographical diversity, Australia has all year round fresh supply of potatoes without the need for long periods of storage. Production is highly intensive and irrigation-dependent with about 500 mm of water during the growing season applied (Beattie 2010). The application of efficient irrigation systems and time-saving farm machinery enables the growers in Australia to pursue economies of scale in area cultivated with ability to attain fairly high yields of about 40 t ha^{-1} (ABS 2014; DPIPWE 2014).

In Tasmania, potatoes are planted between mid-spring and early summer (September – December) with exceptions as dictated by weather conditions. Because of favourable temperature and low levels of aphid borne viruses, potatoes can be grown to senescence and stored "in ground"; harvesting can run from mid-January to July. Cool weather conditions, suitable soils, high water quality and relatively pest and disease free status gives Tasmania State a comparative advantage (Beattie 2010).

Tasmanian potato industry can be classified into three broad sectors; seed, fresh and processing, with processing using 80% of the produce and 10% each for the seed and fresh sectors (DPIPWE 2014). Farmers producing processing potatoes are contracted to the companies Simplot Australia Ltd Pty and McCain Foods, Australia Ltd. Frozen French fries account for over 60% of the total value of the processed vegetable industry in Tasmania with Russet Burbank and Ranger Russet as the main traditional processing cultivars. Other commonly planted cultivars include Moonlight, Bintje, Dutch Cream, Kennebec, Nicola, and Pink Eye. The State has four fresh potato packaging facilities, which supply both the domestic and export market (DPIPWE 2014).

In Kenya, the bulk of the crop is produced in high altitude areas between 1,500 and 3,000 Above Mean Sea Level, (AMSL) with annual rainfall of between 1,050 and 1,900 mm. Potatoes are planted twice in a year; during the March-April-May (MAM) or “Long Rains” (LR), and October-November-December (OND) also known as the “Short Rains” (SR). Production is predominately rain-fed with pockets of irrigated out of season potatoes. Potatoes are grown mainly by smallholder farmers who cultivate between 0.5-6 hectares (ha) per season with few large scale farms (public and private) with about 10 hectares per season. Except for land preparation, farm operations are done manually and in some parts of the country where land is undulating, land preparation is done manually.

Land planted with potatoes in Kenya increased by about 19% from 123,711 ha in 2003 to 152,778 ha in 2013 (FAO 2015). Over the 10-year period, annual average production was 2.3 million tons with the highest national yield of 2.9 million tons recorded in 2008 and 2012. Over the same period, an average yield of 17.7 t ha^{-1} was achieved with the highest recorded yield of 22.4 t ha^{-1} obtained in 2010.

Many aspects of potato production, processing and marketing in Tasmania are quite different from those in Kenya. Growing conditions are significantly different, particularly temperature and photoperiod, two key climatic factors affecting tuber yield (Kooman et al. 1996; Kooman & Rabbinge 1996), rate of biomass assimilation, organ partitioning, specific leaf area, canopy structure, and tuber size distribution and number amongst others. The extent of effects depends on the cultivar and crop management. According to (Kooman et al. 1996), similar varieties grown under same cultural practices give between 20 and 65% of their yield potential when grown under tropical conditions. Longer day length during the cropping season and a cooler climate means Tasmania has a longer growth cycle compared to Kenya. Coupled with good crop husbandry, this could largely explain the higher yields in Tasmania. These and other differences mean impact of climate change on the two systems as well as the adaptation options are likely to vary. Thus, the need to parameterise the model in the two contrasting regions.

Climate change and food security

Projected increase in temperature and changes in rainfall amounts and intensity is predicted to be harmful to potato productivity especially in the tropics where the crop is grown under rain-fed conditions and in the coolest months of the year (Hijmans 2003). With approximately 98% of agricultural sector being rain-fed, Africa’s agricultural systems are among the worlds’ most vulnerable sector to climate change (Boko et al. 2007): potato production systems in Kenya are no exception. In contrast, global warming may be of some benefit to agricultural systems in the State of Tasmania, more so in areas where low temperatures (< 2 ^{o}C) are currently restrictive to crop production as long as the availability and cost of irrigation water is not limiting. Both the positive and negative impacts of climate change will have economic and social implications on potato production and thus the need for adaptation options for potato farmers both in Kenya and Tasmania.

Potato production constraints and opportunities in Australia and in Kenya

Water resources across Australia are generally scarce and as such are highly regulated. Changes in rainfall pattern coupled with increase in atmospheric temperature will exacerbate the water problem in Australia given that in a warmer climate, water demand will increase due to high evapotranspiration rates. For example, in south-eastern and south-western Australia, if the extreme dry scenario of future water projections becomes a reality, agriculture will be negatively affected even in the presence of comprehensive adaptation strategies (Reisinger et al. 2014). In Tasmania with increasing temperatures and growing degree days and a reduction in frost risk, the potato industry is however set to expand into new territory especially as the potato has high water use efficiency. The increased intensity in rainfall as well as longer dry periods will create irrigation challenges for growers and could lead to waterlogging and/or soil erosion.

Despite its role as one of Kenya's strategic food commodity, growth in the potato subsector has and continues to be constrained by many factors including; shortage of quality seed-tubers, limited choice of adaptable high yielding cultivars, high pest and disease incidence, sub-optimal production practices, unreliable rainfall pattern, poor postharvest practices, poor infrastructure, and low value addition. Climate change and climate variability coupled with over reliance on rain-fed growing conditions is an emerging potential threat to the subsector.

In the recent years, a number of initiatives aimed at improving the subsector in Kenya were implemented including introduction of rapid seed multiplication technologies, training of growers in alternative seed production methods and good cultural practices, fast-tracking registration of improved varieties and encouraging private sector involvement. These initiatives improved productivity but the yield gap still exists partly due to low rates of adoption of best practices among farmers (Kaguongo et al. 2013).

Crop simulation modelling can be used to explore constraints as well as to evaluate opportunities and support to a broad range of decision makers involved in the industry and driving agricultural growth both in Tasmania and Kenya. For this to be done, a robust and reliable crop growth model is needed.

Potato productivity modelling

There are over 30 potato crop growth models (Raymundo et al. 2014) and this study chose to use Agricultural Production System sIMulator (APSIM-potato) model. The decision to use the model was based on the extensive application, acceptability and accessibility of APSIM modelling framework. The APSIM model has been widely applied and continues to be used all over the world to answer research questions in a wide range of issues including genotypes-environment-management interactions, land use, soil balance, climate impact and adaptation, cropping systems, species interactions, and breeding (Keating et al. 2003; Holzworth et al. 2006; Holzworth et al. 2014). In addition, there is a growing interest in APSIM modelling framework in African countries including; Kenya, South Africa, Zimbabwe, and Ethiopia where significant APSIM downloads were recorded in 2013/14 (Holzworth et al. 2014). Taking into consideration these attributes and others not presented here, we strongly argue that APSIM-potato model is better placed to be used in potato modelling studies both in Tasmania and Kenya

Prior to this study, APSIM-potato model had been tested and calibrated with a number of data sets from long-term experiment in Lincoln, New Zealand and it accurately reproduced effects of different rates of N-fertilizer, sowing dates, plant density and irrigation treatments (Brown et al. 2011). However, it was recognised that further parameterisation and evaluation was required using field data from different locations and cultivars especially under suboptimal heat and water stress conditions such as Kenya.

Research questions

Continued production of potatoes will play a significant role in assuring food security in many regions. Understanding how a changing future climate will affect potato production is essential in safeguarding the industry that daily feeds a billion people worldwide. This research therefore explores the potential impact of climate change in two geographically distant regions (Kenya and Tasmania, Australia), with different climates, genotypes and management systems.

To investigate how potato productivity may respond to a changing climate, we asked the following questions:

1. Does the APSIM-potato model realistically predict potato phenology and yield under Tasmanian and Kenyan conditions?
2. What are the likely climate change-related impacts for potato productivity in Tasmania and Kenya?

To answer these questions we carried out the following;

1. Collected field data to parameterize and evaluate the APSIM-potato module for Tasmania;
2. Collected field data to parameterize and evaluate the APSIM-potato module for Kenya;
3. Assessed the possible impact of a changing climate both in Kenya and Tasmania;

Thesis structure and outline

This thesis consists of six chapters arranged in interrelated parts that attempt to answer the above research questions addressed in this study. Chapter 1 (this Chapter) outlines the relevant introductory material related to this research. As a basis for understanding the key topics that this research focuses on, Chapter 2 (Literature Review) expounds on: growth and development of potato plant, climate change impacts on food security and on potato productivity, and crop growth simulation modelling. Chapters 3-4 reports on parameterisation and evaluation of the model using measured climate, soil, and crop data both in Tasmania (Chapter 3) and Kenya (Chapter 4).

Following the successful parameterisation and evaluation of the APSIM-potato model, and as a second step in this study, the model was used to assess the vulnerability of the potato in a future changed climate by 2050 and 2100 in the two contrasting environments. The results are presented in Chapter 5. The experimental chapters (Chapter 3-5) are written as stand-alone manuscript for submission to journals. Chapter 6 discussed the results of this thesis and concludes with a framework of future research topics based on the simulation results.

The following terminologies have been used throughout this thesis as defined below:

Model parameterization: The process of determining a set of parameter values deemed suitable for model use in a specific study area (Zeckoski et al. 2015). Malone et al. (2015) defines a parameter as “a distinguishing or defining characteristic or feature, especially one that may be measured or quantified” or “a constant” element or aspect, especially serving as a limit or boundary.

Model validation: Refsgaard (1997) defines validation as the process of demonstrating that a given site-specific model is capable of making sufficiently accurate predictions. This implies the application of the calibrated model without changing the parameter values that were set during the calibration, when simulating the response for a period other than the calibration period. The model is said to be validated if its accuracy and predictive capability in the validation period have been proven to lie within acceptable limits. Validation is an evaluation process that takes a previously calibrated model and tests it with new and independent data.

Model evaluation: Evaluation is the process of assessing the level of precision and accuracy of a calibrated model in reproducing observed data using performance measures and statistical values. Evaluation is necessary in order to build up confidence in a given model or to allow selection of alternative models for modelling studies (Willmott et al. 1985; Janssen & Heuberger 1995; Tedeschi 2006)

Chapter 2 : Literature Review

As a basis for understanding the key topics that this research focuses on, this chapter reviews; (i) the growth and development of the potato (*Solanum tuberosum L.)*; (ii) climate change impact as a threat to food security, impact on potato productivity, adaptation options and opportunities for potato farmers; (iii) crop growth models including potato models and their role in answering the research questions relating to impact of climate change and finally its gives (iv) a summary of the knowledge gaps which this study attempts to address.

Growth and Development of the Potato Plant

The potato plant belongs to the Nightshade (*Solanaceae)* family, is a herbaceous plant, grown for its starchy tubers (shortened and thickened underground stems) ((Bajaj 1987; Allen et al. 1992; Cutter 1992; Ewing & Struik 1992; Gould 1999; Fageria et al. 2010). The tubers which acts as storage organs for carbohydrates and nutrients (Cutter 1992; Carberry et al. 2002; Wohleb et al. 2014), are used both for food, animal feed, industrial uses and for vegetative propagation of the crop (Allen et al. 1992). As a storage organ, mature tubers contain up to 90% of the synthesized starch (Kolbe & Stephan-Beckmann 1997). Tubers may be planted either as a whole tuber or as cut into pieces. For example in Tasmania, Australia, seed pieces (usually weighing 50-60 g and often referred to as seed ‘sets’) (Beattie 2010) are used while in Kenya whole tuber seeds are used. Approximately 9% of the global production in 2013 was used for seed (FAO 2015).

Botanically, the potato plant is classified as perennial crop as it is asexually propagated using tubers but it is considered as an annual crop when grown commercially (Wohleb et al. 2014).

The most commonly cultivated species for human consumption is *Solanum tuberosum L* (Huamán & Spooner 2002; Wohleb et al. 2014). The species *S. tuberosum* which constitutes over 99% of the widely cultivated varieties (Haverkort & Struik 2015), comprises eight cultivated groups *viz Ajanhuir, Andigenum, Chaucha, Chilotanum, Curtilobum, Juzepczukii, Phureja,* and *Stenotomum* (Huamán & Spooner 2002).

As a tool for crop management and on-farm decision making and for research, simulation of plant growth and development is important. Thus for a successful potato crop modelling, it is essential to understand factors that affect growth and development of the potato plant including, the rate and duration of initiation of plant organs, and the rate and duration of organ development and their lifespan (Haverkort & Kooman 1997; van Ittersum et al. 2003; Haverkort 2007). Also, to initialize Agricultural Production System Simulator (APSIM-potato) model, crop specific parameters such as the tuber density, and the management activities such as irrigation, row and intra-row spacing, planting depth and input application are required, (Brown et al. 2011), and hence the need to understand canopy structure.

Potato Canopy Structure

Plant canopy structure, growth and development of the potato plant has been extensively investigated: Vos (1995), Jefferies and Lawson (1991), Cutter (1992), Moorby (1978), Struik and Wiersema (1999), Ewing (1997), Rowe (1993), Wohleb et al. (2014), and many others.

Potatoes are propagated mainly by vegetative seed tubers except in a breeding programme where true potato seed (TPS, the botanically small seeds obtained from the berries) or TPS-derived planting materials (seedling tubers), are used to develop new cultivars (Struik &

Wiersema 1999; Wohleb et al. 2014). Potato tubers have nodes commonly known as “eyes” which contain axillary meristem (buds) that sprouts and grow into stems (Bajaj 1987; Allen et al. 1992; Gould 1999). The eyes are arranged spirally on the tuber (Wohleb et al. 2014). At harvest, tubers are dormant and the buds will not sprout even under optimal environmental conditions (Allen et al. 1992; Cutter 1992), due to hormonal balance of both sprouts suppressors and promoters (Suttle 2004b; Wohleb et al. 2014). Once tuber dormancy is broken, physiologically mature tubers are planted under favourable conditions, sprouts emerge from the eyes and develop into stems.

A stem that grows from a mother tuber is known as a main stem (MS) (Fig. 2.1). Each MS acts independently competing for resources (light, space, water, nutrients) to produce its own roots, stolons, and tubers, and hence the plant population in a potato field is described in terms of stem density (Struik & Wiersema 1999). Roots start to develop at the base of the sprout, usually early and before sprouts emerge on the soil surface while stolons are formed either before emergence(Struik & Wiersema 1999), or 1-2 weeks after emergence (Wohleb et al. 2014). The number of stolons formed is determined by planting depth and spacing, daylength, radiation intensity, temperature, soil moisture and physiological age of mother tuber (Wohleb et al. 2014).

Typically, stolons are underground shoots that tend to grow diageotropically with elongated internodes, spirally arranged leaf scales and a hooked tip. The apical and sub-apical part of the hooked tip is highly meristematic (Cutter 1992). How long a stolon grows before it forms tubers depends on genotype and the environmental factors (Jefferies and Lawson, 1991). Not all stolons will form tubers (Struik & Wiersema 1999). The tuber frequency (% of stolons carrying a tuber) ranges between 20-90% depending on the genotype but it can be more than

100% if there is intensive branching of stolons before tuberization (Struik & Wiersema 1999). The duration between the first and the last tuber to be initiated takes between one or two weeks with variation between genotypes (O'brien et al. 1998).

Based on the genotype, environmental factors and management practices, each MS produces a limited number of leaves before terminating in a flower cluster (Wohleb et al. 2014) (Fig. 2.1). Leaves are compound with terminal leaflets positioned in a spiral phyllotaxis and branching is sympodial (Cutter 1992; Vos 1995; Fageria et al. 2010). Branches from the MS comprises of basal lateral branches (BLB) and apical lateral branches (ALB), both often collectively referred to as sympodial branches(Vos 1995). The BLB can arise either above or below ground while ALB only arises above ground on top of the branch. Each MS and ALB terminates in inflorescence, which either aborts or fully develops into seed (TPS),(Jefferies & Lawson 1991; Struik & Wiersema 1999). Several orders of ALB develop from leaf axis of the "n-1" and "n-2" leaf position and thus ALB are usually identified according to the number of leaf (n-th leaf) on which it branches from and the order of appearance (Vos 1995), (Fig. 2.1).

Once the inflorescence is formed, vegetative growth is taken over by one of the auxiliary buds below the flower cluster; the bud develops into secondary stem and after producing up to six or more leaves, its growth may be taken over by a third stem once it produces an inflorescence (Vos 1995; Struik & Wiersema 1999). Thus the cessation of growth of MS may be not be noticeable as sympodial growth of one or more of the lateral branches below its apex allows further growth above the flower cluster (Fig. 2.1). The number of levels of sympodial growth produced by each MS is primarily determined by the genotype (with variation in determinate and indeterminate types) and to a lesser extent by abiotic factors, physiological age of seed tuber, and agronomic practices (Struik & Wiersema 1999). Determinate types produce fewer levels of branching and tend to be short with shorter growth cycle compared to indeterminate types (Wohleb et al. 2014). However, botanically, potato is determinate since the flowers are borne in the terminal rather than the auxiliary cymes (Fageria et al. 2010).

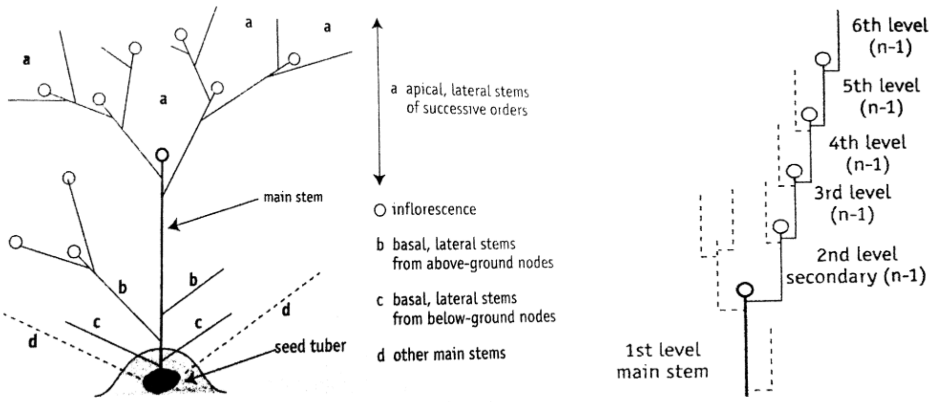

Figure 2.1 Canopy structure of the potato plant showing the main stem (MS) with apical branches with different levels of sympodial growth, above-ground basal lateral branches (AGBLB), below-ground basal lateral branches (BGBLB); Each MS and ALB terminates in inflorescences illustrated as a small circle (Left). Sympodial branching of one MS with different apical branches each producing different levels (Right). Source: Struik and Wiersema (1999).

Phenological Stages of the Potato

Phenological development of the potato is defined primarily by temperature and photoperiod, (Ewing 1981; Haverkort 1982; Prange et al. 1990; Ritchie et al. 1995; Haverkort 2007). The start and end of the growth stages and partitioning of assimilates is temperature dependent while onset of tuber initiation and the length of growing season is daylength dependant, (Wolf et al. 1990; Kooman et al. 1996; Kooman & Rabbinge 1996; Haverkort & Verhagen 2008). Apart from temperature and daylength, intensity of radiation also defines growth and development of potato plant (Haverkort 1990; Haverkort & Kooman 1997). The extent of effects of the growth-defining factors depends on the genotype (Haverkort & Kooman 1997; Haverkort & Verhagen 2008). Plant growth is limited by a suboptimal supply of soil moisture, and nutrients while weeds, pests and diseases are growth-reducing factors (Haverkort & Verhagen 2008).

Nitrogen status of the plant can have a profound influence on the length of growing season. By influencing the level of apical branching and sustained leaf production, nitrogen supply influences the growing period thereby affecting the period of full soil cover when rate of production is optimised (Vos & MacKerron 2000; Bangemann et al. 2014). Excessive N is harmful as it leads to excessive growth of haulms and this may delay tuberization (Vos & MacKerron 2000). In addition growth and development are influenced by crop husbandry practices such choice of cultivar, seed tuber size and quality, farm operations, plant density, and planting date (Rowe 1993).

Growth and development of the potato can be divided into six distinct phenological stages: dormancy, sprout development and emergence, vegetative growth or canopy development, tuber initiation or tuberization, tuber bulking, and senescence/maturation (Jefferies & Lawson 1991; Wohleb et al. 2014), (Fig. 2.2). While these growth stages are true for any potato genotype (Jefferies & Lawson 1991), the timing and duration of each growth stage varies depending on many factors including cultivar, length of growing season, cultural practices, temperature, soil type as well as the market preference (Wohleb et al. 2014). In the Agricultural Production System Simulator (APSIM-potato) model (Brown et al., 2011) used in this study, seven growth stages are considered (dormancy, sprout development, vegetative growth, tuber initiation/early tuber, tuber bulking, senescence, and maturity).

Dormancy

Dormancy or the developmental/metabolic arrest in plants is defined as "the temporary suspension of visible growth of any plant structure containing a meristem" Lang et al. (1987). Potato tuber dormancy is assumed to begin on or about the time of tuber initiation, consequently, tubers are dormant at harvest for zero to over 9 months depending on the cultivar (Suttle 2007). Duration of tuber dormancy is determined primarily by the genetic traits (Wohleb et al. 2014) but also affected by pre- and post-harvest management and environmental conditions (soil moisture, temperature, soil nutrition) as well as the physiological age of tubers (Wiltshire & Cobb 1996; Suttle 2007).

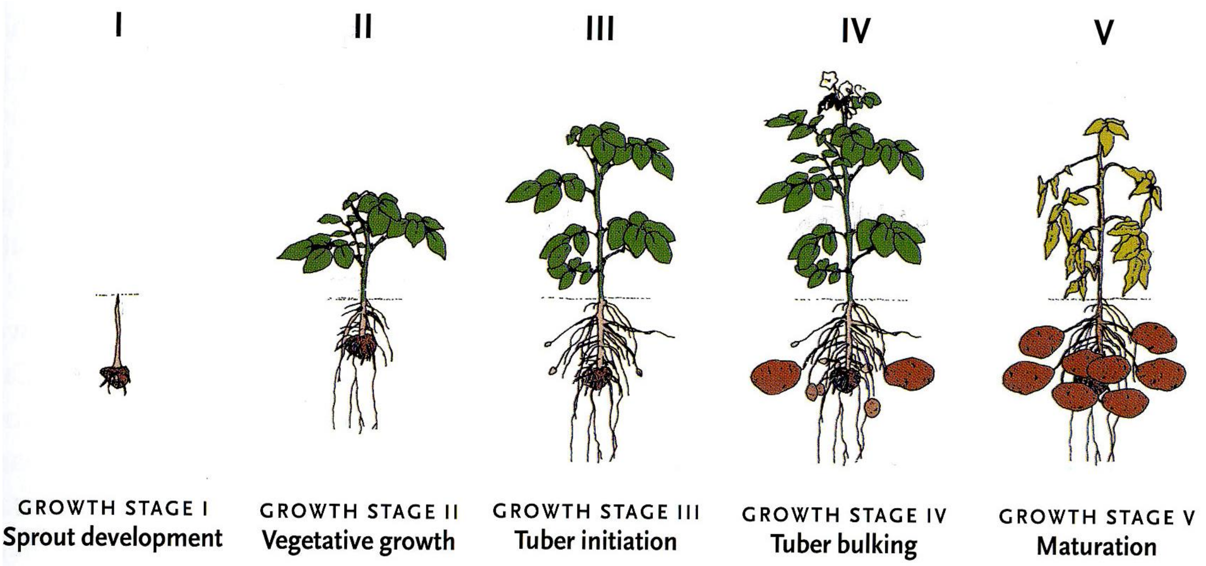

Figure 2.2 The five key phenological growth stages of a potato plant. Dormancy and senescence are not shown. Source: Rowe (1993).

There are two phases of tuber dormancy; rest or innate phase and quiescent or imposed phase (Wohleb et al. 2014). The rest phase is controlled by internal physiological processes (Suttle 2004b; Suttle 2007). A balance of endogenous plant growth regulators and mainly abscisic acid (ABA), ethylene, cytokinins and gibberellins (GA) play a role in control of dormancy (Suttle 2004a; Wohleb et al. 2014). Previous studies have shown that levels of ethylene and

ABA are high in freshly harvested tubers and decline in storage (Suttle 2004a; Wohleb et al. 2014), an indication that these plant regulators promote dormancy though only ABA is required to maintain dormancy (Suttle 2004b). Cytokinins is associated with breaking of dormancy and GA is associated with promoting sprout growth (Suttle 2004b; Sonnewald & Sonnewald 2014). Seed tubers can be treated with GA to accelerate sprout growth during early dormancy (Van Ittersum & Scholte 1993). According to Virtanen et al. (2013), treatment of seed tubers with GA significantly increased the number of sprouts and the number of tubers with cultivar '*Fambo'*.

After the rest period is broken, growth of sprouts can be suppressed by external environmental factors surrounding the tubers particularly temperature (Wohleb et al. 2014). Thus dormancy can be enforced or broken by temperature control, (Blauer et al. 2013; Motica et al. 2015) or by chemical control (Van Ittersum & Scholte 1993; Virtanen et al. 2013). In the absence of chemical control, sprouting increases with increase in temperature while low temperature suppresses sprout growth even after planting the tubers in the field (Wohleb et al. 2014). Between 3 and 25 °C, the duration of tuber dormancy is inversely proportional to storage temperature (Suttle 2007). According to Motica et al. (2015), seed tubers stored at lower temperature (2-4 °C) produced high tuber yields than seed tubers stored in temperature above 7 °C. Storage temperature above 4 °C accelerates tuber respiration thereby increasing physiological age of tubers (Blauer et al. 2013). In temperate regions, seed potatoes are stored for 6-7 months at 3-4 °C and warmed at >7 °C for 7-10 days before planting (Wohleb et al. 2014). Once tubers have broken dormancy and the environmental conditions are conducive (i.e. warmer temperature and supply of water), sprouting will commence. The first bud to sprout after dormancy is broken is the apical bud which is the largest bud on the tuber and often the last to stop growing in the previous season (Moorby 1978). The lateral buds are released from dormancy after the apical bud (hence the term apical dominance) progressively in a basipetal sequence.

Sprouting/sprout elongation and emergence

Sprouting growth stage begins with sprouts developing from the eyes and ends at emergence from the soil. Seed tubers may be planted as pre-sprouts or before sprouting. Sprout length at planting, soil temperature, soil moisture, planting depth and physiological age of the seed tubers determines the rate of sprout growth and hence the time to emergence (Vos 1995). Soil temperature is regarded as the key factor controlling rate of sprout elongation (Midmore 1984). According to Firman et al. (1992), the rate of sprout elongation increases as soil temperature increases from 10 to 20 °C and the rate is higher when there is adequate soil moisture. In APSIM-potato model sprout elongation is assumed to be 1.35 mm/°Cd with soil temperature as the main controlling factor (Brown et al. 2011).

Sprouting potential, (number of eyes that sprouts) of seed tubers is dependent on the genotype and physiological age (Wohleb et al. 2014) while the size of seed tuber determines the number of eyes (Struik & Wiersema 1999). Physiological age is commonly measured as accumulated temperature sum or day degrees, and tuber size is measured either in terms of weight (grams) or in tuber diameter (transverse diameter in mm). Physiologically older tubers typically emerge earlier often with more stems, earlier canopy development and tuberization than the younger tubers (Knowles & Botar 1992; Oliveira et al. 2014). Earlier emergence is advantageous as it leads to early canopy development and increases the chances for optimizing tuber yields. As seed age progresses, apical dominance declines and auxiliary buds increase resulting in more stems, greater tuber set, and shifts in tuber size with variation in genotypes (Blauer et al. 2013). However, the rate of emergence declines beyond an optimum physiological age when tubers are over mature (Vos 1995). Others factors that affect time of emergence include soil depth (Pavek & Thornton 2009), volume and mechanical resistance of soil (Wohleb et al. 2014).

The seed tuber is the sole energy source for growth during sprouting stage until the sprouts emerge from the soil surface, are exposed to light, form leaves and photosynthesis starts (Moorby 1978). Even after emergence, the sprouts will continue to draw reserves from the seed tuber until the reserves are depleted or at approximately 80% weight loss of seed tuber or the seed tuber decays (Moorby 1978); and hence tuber size is an important consideration. Small tubers (less than 20g) will deplete their reserves much earlier than larger tubers (usually 35-80g) thereby affecting both the developing sprout and roots systems (Struik & Wiersema 1999).

Vegetative/ canopy development

Vegetative stage begins at emergence (EM) of the sprouts when photosynthesis begins and ends at tuber initiation (TI). During the vegetative phase, all vegetative parts of the plants (leaves, branches, and inflorescence) develop from aboveground nodes on the stem and stolons that are formed on the belowground nodes of the stems (Wohleb et al. 2014); roots initiation occurs prior to emergence. During the early phases of the vegetative stage, the mother tuber plays a key role but becomes less important as the new plant establishes (Moorby 1978). Once the plant becomes autotrophic, its growth in terms of height, number of leaves and partitioning of assimilates to development organs is determined by the environmental factors (temperature, photoperiod, radiation and atmospheric CO_2 concentrations) (Wolf et al. 1990), water and nutrients supply (Harris 1992; Levy & Coleman 2014) and cultural practices (Pavek 2014).

Tuber initiation/Tuberization

During the tuber initiation stage (TI), the potato plant is growing leaves, stems and tubers. TI is assumed to have taken place when the diameter of the swollen tip is double the 'normal' stolon diameter (Ewing & Struik 1992). Before it starts to form tubers, a stolon undergoes various stages of development which include induction, initiation, rapid growth and branching, cessation of elongation and swelling of the tip (Jefferies & Lawson 1991; Wohleb et al. 2014). Tubers are formed when cells in the sub-apical part of the hooked tip start to expand and the hook is opened and the rate of cell expansion is much higher than the rate of elongation (Wohleb et al. 2014). Tuberization is strongly influenced by temperature, photoperiod, irradiance, and nitrogen levels (Ewing & Struik 1992; Ewing 1995; Jackson 1999). High temperatures and especially night temperature delays or inhibits TI through reduction of assimilates partitioned to tubers and increase of assimilates to other parts of the plant (Jackson 1999). High application of nitrogen reduces the level of tuber induction and if high nitrogen is applied to potato plants after tuberization has commenced, tuberization will stop and stolon growth may be resumed (Jackson 1999), hence the term chain tuberization.

The number of tubers formed is determined by the tuber sites formed, the percentage of the sites on which tubers are initiated and the percentage of initiated tubers that grow to maturity (Struik et al. 1991; Struik & Wiersema 1999). Generally many tubers are formed but not all will develop to marketable size as a number of them are reabsorbed and sometimes relatively large tubers of up to 20 g or 20 mm diameter can be reabsorbed(Ewing 1997; Walworth & Carling 2002). The resorption process involves remobilising and transporting assimilates stored in tubers to other parts of the plant. Based on data from Kirkham (2010) resorption levels range from 27% to 54% for the three cultivars ('Russet Burbank', 'Bintje' and 'Markies') when the number of tubers at TI are compared with the final tuber number. Some of the factors that determine the final number of tubers set include temperature, irradiance, soil moisture, plant health, cultivar, tuber spacing, physiological age of mother tuber and soil nutrients status (Wohleb et al. 2014).

Tuber bulking

Once tuberization is completed and the crop stand is well established, tuber bulking commences and is assumed to have started when 80% of tubers are greater than 10 mm in diameter (Jefferies & Lawson 1991). The rate and duration of the tuber bulking as influenced by canopy size and health status, genotype, soil and air temperature, night and day temperature, photoperiod, irradiance and water supply (Wohleb et al. 2014). During this phase, developing tubers are the dominant sink for water, nutrients and carbohydrates and yellowing of the older leaves begins (Rowe 1993).

Tuber growth is both by cell division and expansion and cell division is the main factor that determines the final tuber size (Moorby 1978). When the growing conditions are optimum and closed canopy, tuber growth is rapid and linear as opposed to expolinear growth during tuberization (Ewing 1997; Fageria et al. 2010). Usually individual tubers grow at varying rates and the biggest tubers at any given time is not necessarily the fastest growing tuber at that given time (Moorby 1978). As such tubers on the same plant exhibit a large variation in size, dry matter content, dry matter composition and physiological age (Struik & Wiersema 1999).

Senescence/Maturity

As the potato plant matures, the levels of chlorophyll in the leaves decreases, photosynthesis rate declines and the senescing leaves turn yellow (Wohleb et al. 2014). Yellowing of the upper leaves of the plants marks the onset of plant senescence (Jefferies & Lawson 1991). When 50% of the upper leaves have turned yellow and abscise from the stems, stems will also turn yellow and eventually the aboveground shoots will die off. In some cases, aboveground shoots may be removed mechanically (pulling, cutting, flaming, rolling) or chemically (using desiccants or herbicides) or a combination before it naturally senesce. This is usually done to control tuber size as in the case of seed potatoes or when tubers have reached the desired market size as in the case of early crop or to prevent pathogen infection (Struik & Wiersema 1999).

As the aboveground shoots continue to senescence, tuber maturation also takes place (Jefferies & Lawson 1991). When tubers are allowed to grow under optimum conditions and are harvested when haulms naturally senesce, buds in the tubers become dormant in acropetal succession and once apical bud become dormant, tuber growth stops. Similarly, if haulms are destroyed prior to natural senesce, tuber growth stop and buds became dormant (Moorby 1978).

Tuber maturity which defines the quality and storability of harvested tubers can be described in terms of physiological, physical and chemical maturity (Sabba et al. 2007). Tubers are considered to be physiologically mature when tuber weight and dry matter content reaches maximum levels and chemically mature when the levels of reducing sugars are minimal. Specific gravity (dry matter content) and reducing sugars are the most important internal qualities of tubers particularly for processing purposes (Harris 1992; Sabba et al. 2007). High dry matter content enhances the texture and crispness of the fried potato products, prevents excessive oil absorption during frying and lowers the susceptibility to sogginess and black spots of the products (Kumari & Agrawal 2014). Low levels of reducing sugars is required for processing tubers to avoid the darkening of fried products due to Maillard browning reaction, which generates acrylamide, a carcinogenic chemical found in potato products fried in high temperatures (Kumari & Agrawal 2014). Other important tuber quality attributes include tuber size and external appearance (skin colour, visible damage, and blemishes) and internal defects. Tuber yield and specific gravity are higher in tubers harvested when haulms are allowed to senesce naturally relative to those harvested when haulms are removed earlier (Virtanen et al. 2013).

Physical maturity commonly referred to as “skin set” is as a result of suberisation of the periderm which causes thickening and hardening of periderm (Sabba & Bussan 2012). Skin set is assumed to have taken place if the tuber skin does not slough when pressure is applied. The strengthened periderm provides protection to the tubers during harvesting and handling. Most importantly, it prevents entry of pathogens to the tuber and water loss and improves its storability (Sabba et al. 2007). Factors affecting skin set include cultivar (e.g. russet-skinned cultivars set skin faster than red-skinned), soil type, time and method of haulm destruction and relative humidity (Sabba & Bussan 2012). According to Virtanen et al. (2013), a combination of chemical and mechanical haulm killing can improve skin set in hot areas where high temperatures affect the skin colour. Depending on the cultivar, soil temperature (21-21 °C is the best), and soil moisture, the process of tuber set takes 10-21 days after the shoots have senesced naturally or when they are killed prematurely (Wohleb et al. 2014).

When haulms are completely dead, mature tubers can lie dormant below the soil surface (i.e “in ground” storage of tubers) before harvesting occurs. However, if mature tubers are left “in ground” for too long, they can become over mature as starch converts back to sugar: this causes a decline in the tuber specific gravity and may cause infection of soil borne disease such as Rhizoctonia (Wohleb et al. 2014).

Climate Change

Global warming due to increased greenhouse gas concentrations in the atmosphere is a continuing process (IPCC 2013). Many of the observed changes since the 1950s are unprecedented recorded history. A warming of global mean surface temperatures (land and ocean) of *ca.* 0.85 °C occurred over the period 1880-2012 when calculated as a linear trend (IPCC 2013). Warming created by the increasing concentration of CO_2 and other carbon-containing gases is accompanied by a rise in sea level, reduction in snow and ice glaciers, and an increasing frequency of extreme events such as floods, droughts, high intensity rainfall, freezing events, and heat waves (IPCC 2013).

Nearly all parts of the world have experienced the impacts of climate change during the last three decades, with 1982-2012 being the warmest period globally since the 1850s and the warmest in the Northern Hemisphere for the last 1400 years (IPCC 2013). The highest mean global temperature for a continuous 12-month period was recorded in 2010 (Hansen et al. 2010). Relative to the period 1850-1900, the increase in global surface temperature for the end of 2100 is likely to exceed 1.5 °C for all Representative Concentration Pathways (RCPs), with exception of the best-case scenario, RCP2.6. RCPs are a new set of emission and concentration scenarios released for the 5th coupled model intercomparison project (CMIP5) (Moss et al. 2010) and adopted by the IPCC for its fifth Assessment Report (AR5) in 2014 (IPCC 2013). RCPs are seen as superior to the Special Report on Emissions Scenarios (SREs) used in AR4 (Nakicenovic & Swart 2000; IPCC 2007), RCPs have four plausible scenarios, corresponding to a specific pathway towards reaching each target Radiative Forcing (RF) in 2100 due to long-and short-lived greenhouse gases. The four RCPs are RCP2.6, RCP4.5, RCP6.0, and RCP8.5 targeting 2.6, 4.5, 6.0, and 8.5 W m^{-2} RF respectively (Moss et al. 2010).

The likely temperature range for 2081–2100 relative to 1986–2005 for RCP2.6 is 0.3 °C to 1.7 °C, with an average of 1.0 °C. In the worst case pathway (RCP8.5), an average of increase of 3.7 °C is projected ranging from 2.6 °C to 4.8 °C, 1.1 °C to 2.6 °C for RCP4.5 and 1.4 °C to 3.1 °C for RCP6.0 (IPCC 2013). Which pathway will be experienced will largely depend on society's collective will to mitigate emissions, but also on scientific endeavour that explores opportunities to mitigate emissions or their consequence within a given region.

Based on Climate Futures Tasmania (CFT), projected rainfall pattern in Tasmania depicts a complex pattern comprising seasonal reductions and increases. In north-west Tasmania where potatoes are grown, a reduction in total rainfall is projected (Grose et al. 2010). Temperatures across Tasmania are projected to increase by an estimated 2.9 °C by 2100 under a high emission scenario (Corney et al. 2010). The CFT project generated the detailed future climate scenarios for Tasmania using five out of the 23 general circulation models (GCMs) used in the AR4, and a sixth model, the CSIRO-MK3.5 (Corney et al., 2010). The six GCMs (CSIRO-MK3.5, ECHAM5/MPI-OM, GFDL-CM2.0, GFDL-CM2.1, MIROC3.2 (medres), and UKMO-HadCM) were selected on objective metrics of the skill of each model in simulating the climate over south-east Australia (Corney et al. 2010).

According to Holz et al. (2010), a warmer climate in Tasmanian will lead to reduction in frost incidence with some areas experiencing less than half of the current number of frost days and increase in rate of accumulation of growing degree days (GDD). Consequently, some crops will mature one to two months earlier relative to the baseline period, 1961-1990. Modelling studies by the same authors under the Climate Future Tasmania (CFT) project indicates a 10 to 100% increase in dryland production by 2085, projected increase in irrigated crops until around 2040, and increase of 10 to 15% increase in wheat as long as essential input particularly nitrogen and irrigation are not limiting. Australian agricultural sector is largely dependent on irrigation, and climate change impacts will depend strongly on water availability and cost (Reisinger et al. 2014).

In the Greater Horn of Africa (GHA) region, climate analysis by Omondi et al. (2014), showed an increase in the frequency of warm nights and days and a decrease in the frequency of cold nights and days over the period 1961-1990. The changes were observed even in the highland areas such as Kericho in Kenya. In Kenya, the highlands areas are the breadbasket of the country and so changes in temperature are likely to affect the agricultural sector including potato, of which the bulk is produced in the highlands.

In terms of rainfall, a wetter OND (October-November-December) and MAM (March-April-May) rainy seasons, and a drier period during the August-September months is projected in eastern Africa (Lobell et al. 2008; Niang et al. 2014). However, other studies have shown the opposite is likely to happen; for example, between 1979 and 2005, MAM rainfall reduced in eastern Africa including in Ethiopia, Kenya, Burundi, and Tanzania, (Funk et al., 2008). These findings corroborates those from a climatic analysis by Omondi et al. (2014), which found an overall decrease in total precipitation for the period 1971-2006 in the GHA region.

The authors argue that there is a significant reduction in the number of wet days receiving more than 1 mm as well as the number of heavy wet days receiving more than 10 mm over the 31-year period. Given agricultural production in most Sub-Saharan Africa (SSA) countries including in Kenya is predominately rain-fed, a reduction in rainfall amounts or changes in rainfall patterns are expected to be harmful to the sector.

Conversely, excess rainfall as predicated in some region may lead to a higher incidence of diseases such as late blight in potato, which proliferates in hot humid conditions. Incidence of disease such as late blight, pink rot, and black leg, can be aggravated by excess water (Pavek 2014). Excess rainfall with flooding may exacerbate spread of soil borne disease from one plant to another (Haverkort & Verhagen 2008) and, may lead to leaching of nutrients such as nitrogen thereby causing water pollution (Herath et al. 2014).

Climate Change: A Threat to Food Security

Crops respond non-linearly to changes in growing seasons and hence impacts, positive or negative, will vary by region, country and location as dictated by the choice of crop, prevailing local climatic conditions, soil types, latitude, topography, technology, and management levels (Mendelsohn 2008; Supit et al. 2010). Mendelsohn (2007) reported that temperature, rainfall and soil types accounted for up to 39% of the crop failures in USA, but temperature alone resulted in approximately 34% of the crop failure rates in various locations. In a global study investigating the effect of climate on four major crops; wheat, rice, maize and soya beans, a 1 °C increase in temperature reduced yield of all crops by up to 10%, with exception of high-latitude countries where crops gain from a longer growing season (Lobell et al. 2011). Equally, soil moisture is crucial to plant growth affecting both yield and yield parameters. Coupled with increase in temperature, projected rainfall amounts and an increased frequency of extreme events such as floods, droughts, high intensity rainfall, freezing and heat waves associated with global warming, is already affecting food security and is projected to have further impact (Hijmans 2003; Lobell et al. 2011; Dwivedi et al. 2013).

There is overall agreement that global climate change will largely have a significantly negative impact on food security (Wheeler & von Braun 2013). Globally, between 2030 and 2049, yield losses across major food crops (maize, rice and wheat), is likely to be more than 25% relative to the late-20th century depending on the region and level of adaptation (IPCC 2014a). Over the same period, about 10% of the projections are likely to gain by up to 10% yield increase relative to late-20th century. By 2050s, yield reduction of major food crops in Africa; wheat, maize, sorghum and millet, are projected to decrease by 17, 5, 15 and 10%; and by 16 and 11% for maize and sorghum across South Asia (Wheeler & von Braun 2013). Rain-fed agricultural systems are more sensitive than irrigated agricultural systems, and hence developing countries which rely predominantly on rain-fed production are more prone, since agriculture is a key driver of their economic growth (Niang et al. 2014).

The most food-insecure countries with low capability to adapt (often those with rain-fed agriculture) are the ones affected most by the recent changes in climate and this is highly likely to continue into the future. Overall, temperate agriculture is more resilient to climate change and increases to temperature which increase yield can be exploited as opportunities through practices such as irrigation and appropriate nutrition, while the opposite is mainly true in the (sub) tropics (Mendelsohn 2008; Lobell et al. 2011).

Climate change thus interacts with non-climate factors to heighten vulnerability of the agricultural sector and thus exacerbate the problem of food insecurity (Van Oort et al. 2012; Niang et al. 2014). The projected impacts of climate change will take place within a framework of a burgeoning population, forecast to reach 8 billion by 2030, and 9 billion by 2050, with the majority of people living in cities and developing countries (Dwivedi et al. 2013; FAO 2013). Consequently, in the face of climate change, the global food requirement is expected to increase by 50 and 70% by 2030 and 2050 respectively.

Given potatoes are easy to cook, are nutritionally rich, and containing carbohydrates, and proteins with low fats, and that more that 50% of the produce is consumed fresh at the point of production (FAO 2008; Lutaladio & Castaldi 2009; Bradshaw & Bonierbale 2010; Navarre et al. 2014), there is no doubt the potato plays and will continue to play a significant role in addressing food security issues.

Despite being a "local for local" crop due to limited cross border trade (Haverkort & Struik 2015), potatoes are consumed by more than a billion people, making it the world's most important tuber and non-grain worldwide (Birch et al. 2012). It can therefore conclude that any negative impact on potato productivity and other major cereals can pose a solemn threat to global food security. In India, one of the leading potato producing countries, potato yields are projected to decline by approximately 6% by mid-21st century, and 11% by end of the 21st century (Kumar et al. 2015). Under this scenario, up to a 25% loss in potato yield is projected by 2060 if no adaptation strategies are applied in Mali (Ebi et al. 2011). Based on data from Resop et al. (2016), a warmer climate will have detrimental effect on both corn and potato with yield declining by an average of 50%, and 19% respectively.

A number of the cited climate impact studies focuses on impacts of climate change without taking in to consideration adaptations options. Adaptations and changes in management and technology will most likely occur to increase production and offset negative impact from climate change. In case of positive impact of climate change, adaptation gains will lead to additional benefits.

Relative to major cereals (wheat, rice and maize), the potato has not received much interest in climate impact studies (White et al. 2011). Yet the crop has a global role as the 3rd most important food crop grown in most continents (Bradshaw & Bonierbale 2010; Birch et al. 2012; FAO 2015). Moreover, potatoes are among the top 50 global commodities that contribute to the top 90% of calories, protein, fat and weight (Khoury et al. 2014; FAO 2015). Many households in Kenya depend on the crop as a source of food and nutrition as well for income generating (Kaguongo et al. 2013). In Australia, potatoes are the leading vegetable and represented about 40% of the total volume, and 19% of the value during a ten-year period from 2002/3 to 2011/12 (ABS 2014).With no specific studies having been conducted, our knowledge on impacts of climate change on potato industry in Tasmania and Kenya are limited. It is important to quantify the impacts under the current potato technologies and ascertain the level of threat on the global most important non-grain food crop.

Potential Effects of Climate Change on the Potato Crop

Effect of increasing atmospheric CO_2 concentration

Between 1970 and 2010, emission from fossil combustion industrial processes contributed over two-thirds of the total Greenhouse Gas (GHG) (IPCC 2014b) with a similar contribution for the period 2000–2010. Increase in global population and economic activities will continue to increase GHG emission with higher atmospheric CO_2 concentrations projected in 2100 relative to present day (IPCC 2014b). Carbon dioxide is a primary substrate of photosynthesis and increase in its concentrations is expected to lead to a CO_2 fertilization effect where photosynthesis is enhanced with the rise in CO_2 (Donohue et al. 2013). Thus crop yield responds positively to increased atmospheric CO_2 concentration but the extent of the CO_2 fertilization depends upon other factors such as species, environmental conditions, irrigation and nutrient applications (Erda et al. 2005; McGrath & Lobell 2013). In addition, food quality could be negatively altered under increased CO_2 concentrations because of higher sugar contents in grain and fruits, and reduction in the protein content in cereals, legumes, and lipid composition (DaMatta et al. 2010; Magrin et al. 2014).

Depending on the species and climatic conditions, CO_2 fertilization effect (per cent increase per 1 ppm increase in CO_2 concentration) on crop yield depicts high variability of 50 to 70% (McGrath & Lobell 2013). Using median model ensemble values from nine different potato crop models tested in two management levels (low and high-inputs), tuber yield increased by 6% per 100 ppm increase in CO_2 levels with more variation in low-inputs systems (Fleisher et al. 2017). In the current study, variability in tuber yield is expected given that two contrasting environment are investigated. Based on data from DaMatta et al. (2010) suggests a higher CO_2 fertilization effect on crop yield of C_3 crops and enhanced water use efficient in both C_3 and C_4 crops under elevated atmospheric CO_2 levels.

In C_3 crops which include potato, rate of photosynthetic carbon uptake is significantly stimulated when grown under elevated CO_2 with yield increase of up to 50% (Long et al. 2006; Leakey et al. 2009). In contrast, C_4 crops would not benefit much from increase in atmospheric CO_2 levels because its photosynthesis is CO_2-saturated at low concentrations as opposed to C_3 species which reguires higher levels of CO_2 concetrations (Long et al. 2006). However, in C_4 crops, increase in the water use efficiency as a result of reduced stomatal conductance may still increase crop yield under elevated CO_2 levels (DaMatta et al. 2010). In a recent study by (Srinivasarao et al. 2016), elevated CO_2 levels significantly increased the root to shoot ratio and biomass yield of both C_3 and C_4 plants but the increase was higher with C_3 crops. In this study plants were grown under three CO_2 levels (ambient at 380 ppm, 550 ppm and 700 ppm).

According to McGrath and Lobell (2013), crop yield enhancement of elevated CO_2 responds nonlinearly to moisture availability, with benefits from greater water-use efficiency only occurring under dry conditions. Using gas exchange theory, Donohue et al. (2013) projected a 5 to 10% increase in green foliage cover in warm, arid environments in responds to a 14% increase in atmospheric CO_2 during the period 1982 to 2010. Many crops (DaMatta et al. 2010; Kumari & Agrawal 2014; Magrin et al. 2014; Kumari et al. 2015; Srinivasarao et al. 2016) potatoes included (Miglietta et al. 1998; Fleisher & Timlin 2006; Fleisher et al. 2013; Kumari & Agrawal 2014; Kumari et al. 2015) have been shown to respond to increase CO_2 concentration with an increased productivity as a result of higher growth rates and better water use efficiency. At higher CO_2 concentrations leaf photosynthetic water use efficiency (WUE) is enhanced resulting in greater net photosynthesis (Erda et al. 2005; Donohue et al. 2013; Kaminski et al. 2014). In addition, a reduction in stomatal conductance under elevated CO_2 will reduce water use (Lobell et al. 2015).

Potato tuber yield increases under elevated CO_2, reliant on nutritional and water limitations (Miglietta et al. 1998; Kumari & Agrawal 2014; Kumari et al. 2015). Yield parameters including fresh and dry weights and number of tubers were higher when grown under elevated CO_2 (570 ppm) combined with Tropospheric ozone (O_3, 70 ppb), compared to plants grown under ambient level of CO_2 and O_3 (382 ppm CO_2 + 70 ppb O_3) (Kumari & Agrawal 2014). Data from the same authors shows effect on tuber quality with an increased in starch content and a reduction in K, Zn and Fe nutrients under elevated CO_2 levels.

Effect of Predicted High Temperatures

The potato is best grown at places where average daily temperature are above 5 °C and below 21 °C (Haverkort & Verhagen 2008; Fageria et al. 2010). Although base temperature in potato growth models is 2 °C (Brown et al. 2011), at a daily average temperatures below 5 °C, growth and development is minimal and there is high risk of night frosts killing the crop (Haverkort & Verhagen 2008). Depending on the growth stage, cultivar, and the plant organ, the thermal optimum for growth varies from 16 to 28 °C: ideal temperature for leaf photosynthesis ranges between 20°C to 24 °C, threshold of 25 °C for leaf expansion, a threshold of 31 °C for stem elongation and a threshold of 27 °C during early tuber bulking (Fageria et al. 2010). A daily average temperatures (day and night) above 21 °C, is assumed to be too hot for potato growth (Haverkort & Verhagen 2008). When exposed to a range of day and night temperatures, maximum individual leaf area values were highest at cooler temperatures, (12-18 °C mean temperature) compared to high temperatures of above 20 °C (Fleisher & Timlin 2006)

Consequently, changes in temperature profiles have a strong impact on tuber yields and higher global temperatures will have a significant impact on what is essentially considered a ‘cool climate’ crop (Schlenker & Lobell 2010). Soil and air temperature are important and often critical environmental factors controlling plant growth and productivity (Fageria et al.

2010). Depending on the crop, higher temperatures may also shorten the length of the growing season and reduce CO_2 assimilation, thereby reducing crop yield (Supit et al. 2010). Albeit, for potato, increasing temperature can be favourable for photosynthetic assimilation, and for every 10 °C increase in temperature, dark respiration in leaves has been shown to double (Ewing 1981), presumably until optimum (T_{opt}) temperature is reached. High temperatures above T_{opt} can incur a number of detrimental changes to potato plant growth (Haverkort 1990; Fageria et al. 2010; Rykaczewska 2015). Beyond this, heat stress and heat induced moisture stress both changes the metabolic balance of the potato plant resulting in less photosynthate becoming available for growth (Ewing 1981).

The level of effects of high temperature depends on the growth stage when high temperatures sets in with more negative impacts on growth and tuber yield when plants are exposed to heat stress at an earlier growth stage (Rykaczewska 2015). Data by Zhou et al. (2017) indicates a reduction in tuber dry matter by approximately 10% per °C as a result of reduction in radiation use efficiency at higher temperatures. Similarly, findings from a model intercomparison study shows that an increase in temperature is detrimental to potato with an average tuber yield loss of 6% per °C increase in temperature based on median model ensemble values from nine different potato crop models (Fleisher et al. 2017).

While photosynthetic efficiency may increase with temperature to a point in some plants, for potato, both growth and partitioning of dry matter to tubers are adversely affected by high temperatures, (Haverkort 1990; Lafta & Lorenzen 1995; Haverkort et al. 2003); it is for these reasons the potato is considered a “cool weather crop” with temperature, genotype, and day length being the key determinants factors for tuberization, (Haverkort 1990). The reduction in net photosynthetic assimilation rates incurred by high temperatures results in low carbohydrate synthesis and delayed onset of both expolinear and linear tuber growth (Van Dam et al. 1996). Also, high temperatures have been found to negatively affect tuber quality by lowering specific gravity (low dry matter content) and producing a paler skin colour (Haverkort 1990). Though day temperatures are important, minimum night temperature are critical for tuberization. Although potato can tolerate temperatures of up to 35 °C (T_{max}), tuberization is reduced by night temperatures above 20 °C, and the plant may fail to set tubers at night temperatures of 25 °C or above (Burton 1989). This is corroborated by a study by Zommick et al. (2014) where bulking of tubers ceased at 29 °C despite high biomass production.

When potato plants were exposed to high temperatures of 35/25 °C (day/night) for a period of 2 weeks during the early growth stages, tuber yield was reduce by over 35% (Rykaczewska 2015). In the same study, exposure of potato plants to high temperature lead to chain tuberization and sprouting of tubers while in the field. In a similar study by (Zommick et al. 2014), high soil temperatures of 23 °C at bulking stage and 29 °C at maturity growth stage resulted in poor processing tuber quality, high reducing sugars and non-uniform fry colour. Relative to a 19/17 °C (day/night) temperature regime in growth chambers during vegetative growth, when plants were transferred to a 31/29 °C temperature regime at tuber initiation, tuber dry matter was reduced by 44% for '*Norchip*', a heat tolerant cultivar, and by 72% for cultivar '*Upto-Date*' (Lafta & Lorenzen 1995). In a similar study under short day conditions by Wolf et al. (1990), partitioning of assimilates to tubers reduced by 14% for-'*Norchip*' and by 50% for '*Desiree*' when grown in a 32/22 °C (day/night) temperature regime relative to a 27/12 °C regime during vegetative growth. The work of Timlin et al. (2006) showed similar trend with '*Atlantic*' having highest tuber dry matter under a constant 20 °C temperature regime, and no measurable tuber dry matter under a constant 32 °C regime. Thus, increase in temperatures via global warming could be detrimental to potato production in some regions.

Conversely, increase in temperature may be beneficial to potato production in other regions (Hijmans 2003). A warmer climate is projected to favour potato production at higher latitudes and in the Peruvian/Bolivian Altiplano region, where low temperatures are currently restrictive (Holden & Brereton 2006; Haverkort 2007; Saue & Kadaja 2011). In these regions, this advantage will result from longer growing period and a reduction in frost damage. Similarly, a modest increase in temperature will be beneficial in parts of Russian Siberia, Canada, and in Scandinavia and in some parts of China, Morocco, South Africa and Lesotho, a warmer climate will allow a shift from autumn and spring to winter potato cropping (Hijmans 2003; Molahlehi et al. 2013). According to data from Pulatov et al. (2015), a warmer climate in northern Europe will enable earlier planting of potatoes and hence earlier harvesting by up to one month thereby reducing the possibility of Colorado potato beetle pest infestation and late blight incidence. However, risk of frost damage during emergence may influence such decisions. From these studies and others, the impact on potato production of a warmer future climate will depend on the location and level of adaptation.

Similalry, thermal treatment through increase in temperature by 2.3 to 5.3 °C will not have a detrimental effect on tuber yield as long as the mean temperature is still within the optimum range (Lizana et al. 2017). According to these authors, tuber yield increased by 11-59% depending on the cultivar and the growth stage at which thermal treatment was introduced.

Effect of Predicted Changes in Rainfall

The potato is widely recognized as more sensitive to water stress (both in adequate and excessive) than many other crops and ample supply of water is needed throughout the growing season for good tuber yield and quality (Van Loon 1981; Gregory & Simmonds 1992; Fageria et al. 2010; Fleisher et al. 2013) . This is partly due to a relatively shallow rooting system, with approximately 85% of roots concentrated in the upper 300 mm soil (Vos & Groenwold 1986; Opena & Porter 1999), although roots can be found down to 1 m depending on the cultivar and soil type. Because of shallow root system, potato has a limited ability to efficiently transport water from roots to stems and leaves (Levy & Coleman 2014). Depending on the climatic conditions and the length of the growing season, potato requires 500-700 mm of water for maximum yields (Lutaladio et al. 2009).

Plant transpiration and photosynthesis are negatively affected by suboptimal water supply, with insufficient soil moisture leading to stomatal closure reducing CO_2 uptake, and presumably due reduced evaporative cooling from transpiration, increased respiration rates associated with higher leaf temperatures (Haverkort 1990; Levy & Coleman 2014). While all the six stages of potato development are sensitive to water stress, tuber initiation and tuber bulking are most sensitive stages (MacKerron & Jefferies 1988; Haverkort 1990; Yuan et al. 2003; Levy & Coleman 2014). Importantly, tuber yield and quality are adversely affected even by relatively mild water stress (Onder et al. 2005). If tuberizing potato plants are exposed to water stress, the partitioning of assimilates is altered leading to reduced start synthesis, increased sucrose levels and reduced dry matter (Levy & Coleman 2014). Other observable effects of water stress in potato plants include reduced canopy development due to reduced leaf size, leaf formation and leaf expansion and accelerated rate of leaf senescence

(Jefferies & MacKerron 1993). Cultivars respond differentially to this, some being more tolerant than others (Gregory & Simmonds 1992).

Potatoes are also sensitive to excess moisture as depletion of soil atmosphere O_2 changes limits growth maintenance respiration, adversely affecting growth and tuber yield. In an Estonian study by Saue and Kadaja (2014), the highest losses in tuber yield was observed in years with excess water, while in the Netherlands, Van Oort et al. (2012) singled out a “wet start” of the growing season and a “wet end” of the growing season as the key weather extremes that explained anomalies observed in potato yields recorded between 1951-2010. Predicated changes in rainfall whether a reduction or an increase in amounts or changes in rainfall pattern, and intensity will affect potato production either positively or negatively or may remain unchanged. Compared to high-input systems with intensive irrigation and optimum fertilizer application, productivity of rain-fed potato systems will be affected most by changes in rainfall pattern. At low-input trial sites, tuber yield decreased by 2% for every 10% decrease in rainfall and increased by up to 26% in response to increasing rainfall (Fleisher et al. 2017).

Effects on Pests and Diseases

The impacts of climate change on plant pathogen and disease load have been extensively examined for major food crops including the potato (Table 2.1). In a warmer climate and with high humidity, late blight is projected to increase and expand to high altitude areas above 3000 AMSL, such as in the Andes region where it is currently absent (Boland et al. 2004; Hannukkala et al. 2007; Luck et al. 2011). Recent changes in climate are already affecting infection and incidence of late blight; for instance in Ireland, the risk of late blight was 17 times higher and disease outbreaks started 2 to 4 weeks earlier between 1998 and 2002 relative to the periods 1933-1962 and 1983-1997 (Hannukkala et al. 2007). When plants are infected at an early developmental stage, more severe disease symptoms will develop and in the case of late blight in Ireland, this translated to more fungicides applications during the 1980s to 2002. These results are in agreement with simulations in southern Finland where a rise of 1 °C in temperature is reported to lengthen the infection duration by 10-20 days (Kaukoranta 2008).

Elevated temperatures combined with high rainfall events such as flooding will increase the spread and infection of potato bacterial diseases from infected plants or soil, this exacerbated by rain splash or runoff (Haverkort & Verhagen 2008; Luck et al. 2011). These diseases include bacterial wilt, Dickeya, black leg, and common scab. Colorado potato beetle and PCN are also projected to increase in a warmer climate (Luck et al. 2011). Under temperate climates and in high altitude regions, elevated temperatures will favour spread and reproduction of viral vectors such as aphids and the survival of alternate host plants will increase under milder winters (Boland et al. 2004). Viruses are a major tuber yield-reducing factor in Kenya and aphids are found even in high altitude areas above 2500 AMSL (Were et al. 2013). According to Kroschel et al. (2013), infestation of potato fields with PTM will increase from the current 30% to 42% of the total land planted with potatoes by 2050.

The evidence from these studies strongly supports the assertion that the spectrum of pests and diseases will change in many of the potato growing regions under a warmer climate. This underpins the need for a breeding programme for pest and disease resistance and adaptation. The International Potato Center (CIP) under Late blight resistant (LBHT) and the Lowland subtropics resistant (LTVR) programme has developed genotypes with tolerance to heat under both arid and humid conditions, and resistance to viruses, particularly PVY and PVX, and increased quantitative resistance to PLRV and late blight tolerance (Gastelo et al. 2014). The two advanced clones used in this study were selected from the LTVR population: CIP accession number 392797.22 and CIP accession number 300046, both of which had performed well in previous trials, and offer possible adaptation options in a warmer future climate for farmers in Kenya.

Table 2.1 Projected net positive or negative impacts of climate change on major potato pests and diseases and the main reason for anticipated change

Common Name	**Pest/disease scientific name**	**Effect of climate change**			
		Main reason for anticipated changes	**Projected net effect**	**Location of the study**	**References**
Canker	*Rhizoctonia solani*	rate of disease progress is reduced	decrease	Ontorio, Canada	Boland et al. (2004)
Early blight	*Alternaria solani*	rate of disease progress is reduced	decrease	Ontorio, Canada	Boland et al. (2004)
Late blight	*Phytophthora infestans*	infection duration is lengthened	Increase	Ireland Finland	Hannukkala et al. (2007) & Kaukoranta (2008)
Pink rot	*Phytophthora erythroseptica*	rate of disease progress is reduced	decrease	Ontorio, Canada	Boland et al. (2004)
Verticillium wilt	*Verticillium spp*	rate of disease progress is increased	increase	Ontorio, Canada	Boland et al. (2004)
Blackleg	*Pectobacterium carotovorum*	rate of disease progress is reduced	decrease	Ontorio, Canada	Boland et al. (2004)
Ring rot	*Clavibacter michiganensis*	rate of disease progress is reduced	decrease	Ontorio, Canada	Boland et al. (2004)
Potato leaf roll virus (PLRV)	Viral	increased survival of insect vectors	Sig. increase	Global view	Luck et al 2011 Boland et al. (2004)
Bacterial wilt	*Ralstonia solanacearum*	increased inoculum population and spread	increase	Global view	Haverkort and Verhagen (2008)
Soft rot	*Pectobacterium chrysanthemi*	increased inoculum population and spread	increase	Global view	Haverkort and Verhagen (2008)
Common scab	*Streptomyces scabies*	rate of disease progress is increased	increase	Ontorio, Canada	Boland et al. (2004)
Potato tuber moth (PTM)	*Phthorimaea operculella*	increased survival and invasiveness of PTM	increase	Global view	Kroschel et al. (2013)
Colorado potato beetle	*Leptinotarsa decemlineata*	increased survival and invasiveness	increase	Global view	Jeffree and Jeffree (1996)
Potato cyst nematode	*Globodera rostochiensis*	increased survival and invasiveness of PCN	Increase	Global view	(Haverkort and Verhagen, 2008)

Adaptations Options for the Potato Growers

In the absence of adaptation, global potato yields are projected to decrease by up to a third by 2050 depending on the region, compared to 9 to 18% with adaptation in 2040-2069 (Fig. 2.3) (Hijmans 2003). Potato growers have four broad options for adapting to changed growing conditions and seasons; (i) change the planting dates to suit the prevailing conditions; (ii) move to new areas such as higher altitudes; (iii) if the first two options are not possible, farmers can apply sustainable agricultural practices, technologies and innovations such as heat and water stress tolerant cultivars, and irrigation, or; (iv) in a worst case scenario, abandon cultivation of potatoes: for example farmers in Sikasso area in southern Mali will have to consider diversifying out of potato cultivation if the growing conditions continue to become unfavourable due climate change (Ebi et al. 2011).

The choice of adaptation options (Table 2.2) selected by farmers would depend on what is within their disposal and the perceived cost and benefits associated with the choice (Burke & Lobell 2010). While they are easier and cheaper to implement, autonomous adaptation options such as shifting planting dates or moving to new areas may be restricted by other non-climatic factors such as competition from other crops or lack of access to markets (Burke & Lobell 2010). Also, as the potato plant is photoperiod sensitive, shifting planting dates may expose the crop to day lengths deleterious to its growth and development (Hijmans 2003). Similarly, as the potato requires a minimum accumulated thermal time of at least 1250 day degrees for one growth cycle (Haverkort & Kooman 1997), shifting planting dates in some regions may mean this accumulated heat unit threshold is not met.

Expensive measures such as development of the potato cultivars with increased heat and disease resistance and the expansion of irrigation appear to be appropriate no-regret options to cope up with climate change (Lobell et al. 2008). Compared to other cultivars, heat resistant cultivars have been reported to have higher tuber yield under heat and water stress conditions. In China, cultivar "*Jizhangshu 8*", a CIP-bred clone (CIP Accession No.390478.9, known as Tacna in Peru), with drought, heat, and salinity resistance, has been widely adopted in drought prone areas of the country since it was registered 2006 (Carli et al. 2014). This is a good example of how adoption of heat resistance cultivars can substantially attenuate the negative impacts of climate change on potato yields.

Introduction of supplementary irrigation at the most sensitive growth stages is critical in a rain-fed production system such as in Kenya. In areas where a modest increase in temperature is likely to favour potato production, demand for irrigation water is likely to increase due to an associated increase evapotranspiration. For example in Ireland, the cost and availability of irrigation water will increasingly become a limiting factor for potato production (Holden et al. 2003). If the surety of access to irrigation water can be provided, then potato yields will continue in high latitude areas. However, there are very limited options for potato farmers in the (sub) tropics due to a lack of infrastructure or inefficient irrigation practices, and potato production is already taking place during the coolest season (Hijmans 2003). Taking into consideration these possibilities, there is need to assist the domestic industries of both Tasmania and Kenya, keeping them informed and providing guidance in the future use of precious resources such as water, through sound crop management advice assisted by comprehensive government policy.

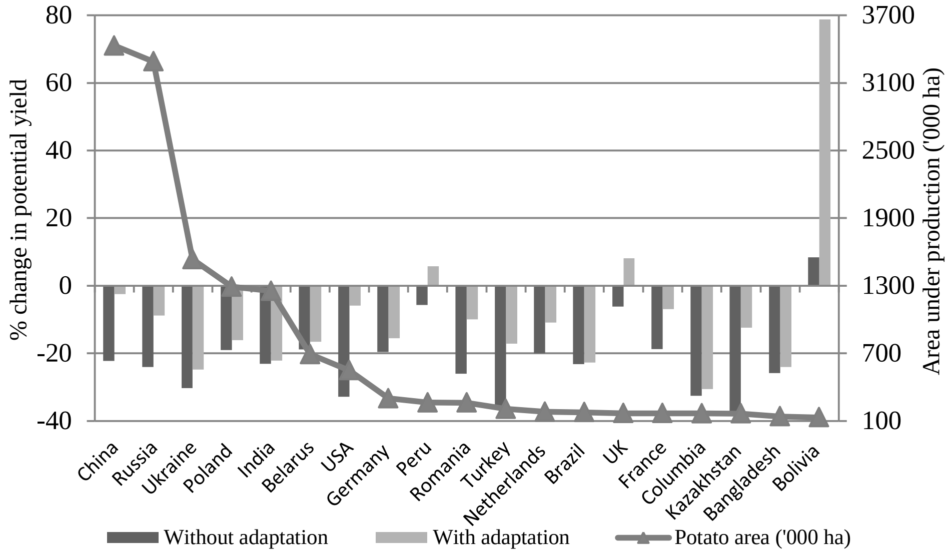

Figure 2.3 Area ('000' ha) under potato in major global potato producing countries and projected change (%) due to global warming (with adaptation and without adaptation) in potential tuber yield for the period 2040-59. An increase in global temperature of 2.1 °C to 3.2 °C was used to project the changes in tuber yield in the study countries. Source: Hijmans (2003)

Table 2.2 Autonomous farmer adaptation options to reduce the negative impacts or explore positive impacts of climate change and conditions determining the applicability of each adaption option. Adapted from Burke and Lobell (2010)

Adaptation option	**Where it might be applicable**	**Where it might not applicable**
Shift planting date	Growing period is lengthened	Current growing season length is not limited by low temperatures
Switch cultivars	Other cultivars better suited to new climate are available.	Cultivars that are more suitable are not always available.
Switch crops/diversify crop	Other crops more suitable to new climate are available.	Hotter countries often do not always have many alternatives
Expand area	Climate change might expand suitable area.	Limited in the tropics due to soil constraints and expansion may come with significant environmental losses.
Expand/introduce irrigation	Quality water for irrigation is available.	Can be quite expensive often requiring public investment. Many places have limited water resources. Warming increases evapotranspiration.
Diversify income	Non-farm income sources are less vulnerable to climate change.	Rural non-farm economy is linked to agricultural activities.
Migrate	Areas not adversely affected by climate change available.	Urban areas are already strained.

An Overview of Crop Growth Models

Pioneered by De Wit (De Wit 1958), the concept of crop modelling started about six decades ago. Currently, hundreds of crop growth models have been developed and are available for nearly all major crops (White & Hoogenboom 2010). There are two broad categories of crop growth models (referred hereafter as crop models); the less complex empirical regression models, and the detailed mechanistic models. Empirical models describe crop growth on the basis of light interception and utilization, and dry matter distribution on the basis of a harvest index, whilst describing crop growth based on underlying physiological processes in response to environmental factors forms the core concept in mechanistic models, these also referred to as proceed-based, physiological or explanatory models (Spitters 1990).

The three types of environmental factors that determine crop yield and which are considered in crop modelling are; growth-defining factors, growth-limiting factors and growth-reducing factors (Haverkort & Kooman 1997; van Ittersum et al. 2003). Growth-defining factors including radiation intensity, CO_2 concentration, temperature and crop traits determines the maximum or the potential yield that is achievable in a given physical environment and for a given plant species. Growth-limiting factors are water and nutrients and they determine limitations on production in a given physical environment. Biotic factors including weeds, pests and diseases are the growth-limiting factors which reduce or impede plant growth.

A basic crop model requires that initial soil water and nutrient conditions, management events and climatic factors such as temperature, solar radiation, and precipitation specified in order to run a simulation. Crop models integrate a series of mathematical equations to simulate the effects of environmental factors on plant physiological, physical and chemical processes that determine plant growth and development (White & Hoogenboom 2010). Some of the plant processes (Table 2.3) that are modelled include; photosynthesis, respiration, biomass partitioning, phenological stages, transpiration, and water and nutrient uptake.

Crop models are mainly used for three broad problem domains, to; (i) understand research such as genetic improvement for enhancing adaptive capacity of crops in current or future climatic conditions; (ii) make on-farm decisions such as choice of varieties, when to plant, when to irrigate as well as predict fertilizer requirement and crop performance; and (iii) formulate policies (Boote et al. 1996). The use of crop models in combination with climate models is increasingly becoming an indispensable tool for projecting impacts of climate change on the agricultural sector under various future scenarios, and evaluating adaptation and mitigation strategies. However, most crop models do not account for the extreme weather events predicted since most models were originally designed to simulate plant growth and development under prevailing climate conditions, (Gobin 2010; Wheeler & von Braun 2013; Angulo et al. 2013.).

Another limitation when using crop models to simulate regional yields is that the models do not fully capture the spatial variation in soil-water-management interactions. Some models do not efficiently simulate the effect of CO_2 on plant growth and others do not capture the effect of climate change on yield quality (Boote et al. 2013). It is therefore, vital that careful selection of a model to be used for investigating the future impacts of climate be done. The current study selected Agricultural Production System Simulator (APSIM) model. The APSIM, an elaborate agricultural systems model, has addressed most of the above limitations (Holzworth et al. 2014). It has been used successfully to investigate the impacts of climate change on agriculture, as well as adaptation and mitigation strategies, to assess effects of changes in atmospheric CO_2 concentration, temperature and rainfall pattern on different scenarios and to address quality components of produce, e.g. protein content of wheat grains (Holzworth et al. 2014). Thus, it can be concluded that APSIM is a good choice of a model for undertaking climate change impact studies, and it is for this reason that the current study used the model to assess potential impacts of a future climate on potato productivity in both Tasmania and Kenya.

Table 2.3 Effects of selected environmental factors on simulated plant processes. Adapted from White and Hoogenboom (2010)

Factor	Process	Extent to which the process is modelled	Effects/Comments
Temperature	Phenology	Full	Warming normally reduces time to flowering and maturity, but high temperatures may delay development.
	Photosynthesis	Full	Heat stress is poorly understood and seldom explicitly modelled.
	Respiration	Full	PS rate increases with temperature.
	Leaf development	Partial	Models differ greatly on how temperature affects leaf expansion and thickness.
	Reproductive growth	Partial	Heat stress is poorly understood and seldom explicitly modelled.
	Root elongation	Full	Rate increases with soil temperature, but soil temperatures are poorly modelled, including under climate change.
	Potential evapotranspiration	Full	Potential water loss increases with temperature, and is accurately predicted by Penman-Monteith equation (ref).
	Mineralization of soil organic matter	Full	Rates increase with soil temperature.
CO_2 Concentration	Development	Not	Effects vary with species and are not adequately understood for modelling.
	Leaf development	Not	Not well enough understood to be modelled.
	Photosynthesis	Full	Basic response to CO_2 is well described by Farguhar model (ref) but controversies remain.
	Respiration	Not	Not fully accepted as existing physiological mechanisms are poorly understood.
	Transpiration	Full	Cultivar differences are likely but not considered in current models.
Solar radiation	Photosynthesis	Full	Leaf and canopy responses are well described by models.
	Leaf development	Partial	Few models consider leaf expansion and thickening.
	Potential evapotranspiration	Full	Potential water loss increases with radiation as accurately predicted by

Factor	Process	Extent to which the process is modelled	Effects/Comments
			Penman-Monteith equation.
Wind	Potential evapotranspiration	Partial	Potential water loss increases with wind, as accurately predicted by Penman-Monteith equation.
Relative humidity	Leaf development	Not	Not well enough understood to be modelled.
	Potential evapotranspiration	Partial	Potential water loss decreases with humidity as accurately predicted by Penman-Monteith equation.
	Transpiration	Partial	Direct plant responses to humidity, including cultivar responses are poorly understood.

An Overview of Potato Crop Growth Models

The first potato model, Sands Model, was developed about four decades ago (Sands et al. 1979). Since then, over 30 potato crop growth models have been developed and used for a range of systems application including impacts of climate change (Raymundo et al., 2014). Some of commonly used potato models are; SIMPOTATO, LPOTCO, SUBSTOR-Potato, POMOD, and LINTUL-Potato (Raymundo et al. 2014). Others are Potato Calculator, POTATO, SOLANUM, WOFOST, Johnson-Potato model, Infocrop-Potato and APSIM-Potato. Based on the literature, LINTUL-Potato and SUBSTOR-Potato are the most widely tested and applied potato models and APSIM-potato is one of the least tested and applied potato models.

When partitioning dry matter, a potato model will give priority to tuber organ assimilate demand while considering the variable source-sink relationships occurring during various stages of tuber growth (Kooman & Haverkort 1995). There are, however, shifts in the source–sink relationship throughout the growing season and it is strongly influenced by cultivar, environment, and plant nutrient status. There are three distinguished tuber growth stages; early stage of plant growth when tuber sink strength is limited; the second phase when tubers are competing with other plant organs; and the final stage when tubers are the dominant sink (Kooman & Haverkort 1995). At initialization, most of the potato models require input of the management events including date of planting, spacing, irrigation (if any) and fertilization (N & P fertilizer) and very few models (e.g. Johnson-potato model) requires seed size of the tubers.

The opinion of Raymundo et al. (2014) and Fleisher et al. (2017) is that most of the potato crop models have not been comprehensively tested with actual field data, yet this is a key prerequisite for using models in climate impact studies. For example, the first results quantifying uncertainty for potato were reported by Fleisher et al. (2017). According to these authors, climate change impact modelling studies on potato can be enhanced by using an ensemble approach. Raymundo et al. (2014) outlined three steps needed before using potato models to investigate the impacts of climate change on tuber yields.

First, potato models should be calibrated under varied climatic conditions using improved cultivars. Secondly, the model's capability to simulate the effect of growth-defining factors and management on plant growth, phenology, and partitioning from planting to maturity should be evaluated. Thirdly, the models should be tested with field data, evaluating their ability to simulate crop response to increased CO_2 concentration under heat and water stress in combination with elevated temperatures. It is for this reason that the current study set up field trials to calibrate the model under local conditions both in Tasmania and Kenya. These two locations offer a varied and contrasting climatic conditions and management levels.

Agricultural Production System Simulator (APSIM) Model

The Agricultural Production System Simulator (APSIM) Model is an agricultural systems model developed by the Agricultural Production Systems Research Unit (APSRU) in

Australia in 1990s (Keating et al. 2003). Over the years, the APSIM has evolved from the initial version (version 1.61 released on 30th May 2000), a cropping system model which was restricted to single point simulation (Keating et al. 2003) to the current version (version 7.7 released on 12th December 2014), an agro-ecosystem model that has multi-point (multiple location) capability. To broaden its industry scope and in response to growing demand by researchers, farmers and policy makers, several external models have been built into APSIM and new features have been incorporated over time (Holzworth et al. 2014).

The APSIM modelling framework (Fig.2.4) has four key elements; (i) a set of biophysical modules that simulates biological and physical processes in farming systems; (ii) a set of management modules that allow the user to specify the intended management practices characterizing the scenario being simulated; (iii) different modules to facilitate data input and output to and from the simulation, and; (iv) a central engine that drives the simulation process and controls the independent modules (Keating et al. 2003). These modules have the capacity to simulate efficaciously the biophysical processes within the context of defined farming systems to capture projected yield, economic and ecological effects, and the outcomes of specific management practices.

There are approximately 60 biophysical modules within APSIM that are broadly grouped into plant, animal, soil and climate models. The majority of modules are plant models, representing about a third of the total modules. Plant models simulate potential yields, water-and-nutrient limited yields, and actual yields by capturing key plant physiological mechanisms such as phenology in response to growth-defining, growth-limiting and growth-reducing factors (Keating et al. 2003). The plant models partitions dry matter assimilates into four state variables; leaf, stem, root and grain organ. Specific plant models are available for a wide range of cereals, legumes and pastures, sugarcane, cotton, horticultural crops (sweet corn, green bean, lettuce and potato) and forest. Also available is a generic model for weed competition (Holzworth et al. 2014). While majority of the APSIM crop models have been extensively tested and validated and are progressively been used globally, some of the models including the potato–model (Brown et al. 2014) have not been widely validated.

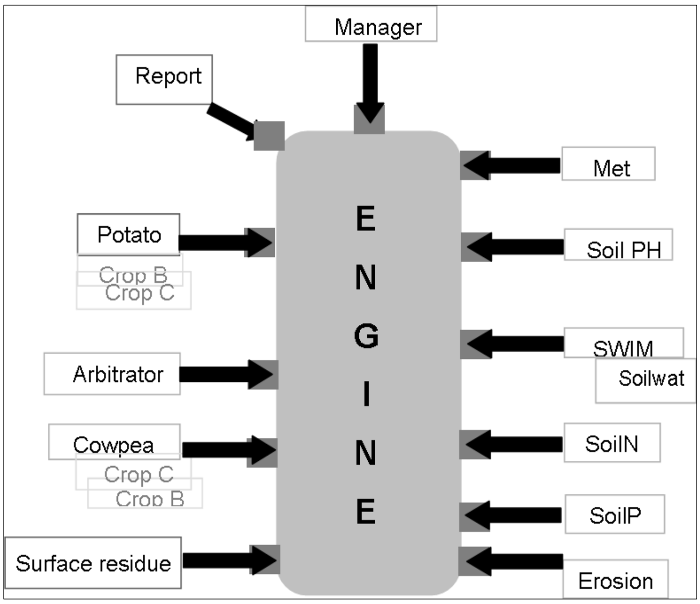

Figure 2.4 Diagrammatic representation of the APSIM modelling framework with individual modules that can readily be pulled-out or plugged-in. Framework in this context refers to the set of structures that support the higher order goal of farming system simulation. Adapted from http://www.apsim.info/wiki/APSIM-Model.ashx

APSIM is recognized as a robust system model that has been widely applied, and continues to be used across the key problem domains worldwide (Keating et al. 2003; Holzworth et al. 2014). Initially developed by scientists for scientific use, its user base has expanded over the years to include analytical, operational, academic and practical use without compromising scientific values. Farmers, agribusiness, agronomists and consultants have equally used APSIM to assess the viability of their business. APSIM has also been used as a teaching tool both for graduate and post-graduate levels of education (Holzworth et al. 2014). “Crop Arm”, "Howet?" and "Yield Prophet" (Holzworth et al. 2006; Holzworth et al. 2014) are three APSIM derived products under the newly introduced concept of "run anywhere" designed to meet agronomist's, farmer's, and consultant's needs.

The demand for and wide acceptance of APSIM not in only Australian farming systems but also other parts of the world demonstrates its reliability and robustness (Keating et al. 2003). In 2009, APSIM was ranked among the 18 biophysical models that were found to have high potential to give immediate analysis of vulnerability to climate change within Australian agriculture (Pearson et al. 2011). Ranking was based on six criteria: scope, scale, operation status, accessibility, validation and data availability.

APSIM-Potato Model

The APSIM-potato model is a comprehensive daily time-step, deterministic crop model (Brown et al. 2011; Brown et al. 2014). It integrates with the APSIM soil, SOILN, management and user interface components to provide a robust and user friendly crop model. The APSIM-potato model predicts dry matter (DM) yield, yield parameters, and N uptake of the potato plant as well as soil water interactions during the growing seasons, these estimated on a daily basis in response to inputs of daily weather data, soil characteristics, crop parameters and management actions. Total daily DM production is estimated from the product of incoming solar radiation (*Radn*), radiation interception (*1/10*), the fraction of radiation that the crop intercepts, radiation use efficiency (*RUE*) and stress factors (water (f*w*), temperature (*ft*) and atmospheric carbon dioxide concentration (fco_2)) as follows:

$$\Delta DM = Radn\ x\ {}^{I}/_{Io}\ x\ RUE\ x\ fw\ x\ ft\ x\ fco2 \qquad (1)$$

Radiation interception is calculated from predictions of leaf area index (LAI) and light extinction coefficient (k). LAI and k (a constant value of 0.8) are the main crop specific parameters that most influence interception of solar radiation. The value of k is related to the leaf inclination angle, leaf arrangement and the LAI and it provides an indication of the plants efficiency on intercepting radiation. The model uses a phytomer-type canopy model to estimate the LAI. Using inputs of tuber planting density and the number of stems per tuber, the model calculates the population density of primary stem units, which are in turn used to predict the rate of appearance, expansion, size and life span of individual leaves on the main stems and, the rate of branching. The APSIM-potato model then partitions the dry matter assimilates produced into the four state variables; leaf, stem, root and tuber. The minimum data input required to run a simulation in APSIM-Potato model are presented in Table 2.4.

Table 2.4 Input data set required to run the APSIM-Potato model

Data	**Abbreviation**	**Units**
Soil properties		
Initial soil water content (layered)	Sw	%
Bulk density	BD	g cc^{-1}
Crop Lower Limit	CL15	mm mm^{-1}
Drained Upper Limit	DUL	mm mm^{-1}
Vol. water content at saturation	SAT	mm mm^{-1}
Initial soil-N (layered)	-	Kg ha^{-1}
Initial soil chemical	-	-
Soil surface characteristics	-	-
Daily weather		
Solar radiation	Radn	MJ m^{-2}
Temperature	Tmin & Tmax	°C
Precipitation	-	mm
Crop management events		
Sowing date	-	-
Sowing depth	-	mm
Tuber/set rate	-	tubers m^{-2}
Main stem density	-	stems m^{-2}
Irrigation	-	mm day^{-1}
N and other fertilizer	-	Kg ha^{-1}

For evaluation purposes, the APSIM-potato model output data that can be compared with observed/measured data are summarized in Table 2.5.

Current limitations of APSIM–potato model

Whereas the APSIM-potato model has previously been tested and calibrated with a number of data sets from long-term experiment in Lincoln, New Zealand, and has accurately reproduced effects of different rates of N-fertilizer, sowing dates, plant density and irrigation treatments with 'Russet Burbank'. However, it was recognised that further parameterisation and evaluation was required using field data from different locations and cultivars than 'Russet Burbank' (Brown et al. 2011). Other research gaps identified include, the need to; (i) refine phenology so as to capture the effects of day length on main stem leaf number; (ii) conduct more testing of its performance under suboptimal heat and water stress conditions and, (iii) develop a reliable method for estimating cultivar specific parameters. In Kenya, this study also addressed the need to test model performance under suboptimal heat and water stress conditions.

Table 2.5 Observed and predicted data that can be used to evaluate performance of APSIM-Potato model

Data	Abbreviation	Units
Soil water and nitrogen variables	-	
Soil water	-	mm
Soil-N		g m^{-2}
Phenology	-	
Date of emergence	-	days
Sprouting	SC2	days
Vegetative	SC3	days
Early Tuber	SC4	days
Late tuber	SC5	days
Senescence	SC6	days
Maturity	SC7	days
Canopy	-	
Leaf Area Index	LAI	m^2 m^{-2}
Leaf appearance	-	-
Height	-	mm
Biomass partitioning	-	
Leaf, stem and tuber fraction	Livewt	g m^{-2}
Biomass (stem and leaf)	Livewt	g m^{-2}
Tuber dry matter yield	Livewt	g m^{-2}
N- uptake (leaf, stem and tuber)	LiveN	g m^{-2}

Addressing the potato modelling gap

Overall, the literature review has shown that potato is likely to be affected by predicated increase in temperature and $CO_{2,}$ concentration, changes in rainfall intensity and pattern. Further the literature review revels that climate change impacts studies on potato crop lack behind other major crops and that site specific impact studies have not been conducted in both Tasmania, Australia and Kenya yet potato plays a key role in the economies of the two regions.

Consequently, our knowledge on impacts of climate change on potato industry in Tasmania and Kenya are limited. And though previous studies seem to indicate a potential gain in Tasmania and loss in Kenya, it is important to quantify the impacts under the current potato technologies and ascertain the level of threat or opportunities arising from climate change on the global most important non-grain food crop. Also the literature review shows that use of crop models in combination with climate models is increasingly becoming an indispensable tool for projecting impacts of climate change on agricultural sector under various future scenarios and evaluating adaptation and mitigation strategies.

The study was designed in such a way that once the model is successfully parameterized and evaluated, it can be used to assess the impact of climate change on potato productivity, analyse the constraints facing the potato industries, and explore opportunities for the betterment of the industries in each country. Importantly, the study aimed to compare the performance of the model under two contrasting environments and management levels; the industrialised high latitude, high-input production systems under a cool temperate climate in Tasmania, and the small-scale low latitude, low-input systems under tropical highland conditions in Kenya.

Chapter 3 : Improving the prediction of potato productivity: APSIM-Potato model parameterization and evaluation in Tasmania

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Abstract

We evaluated the ability of the APSIM-potato model to predict biomass, tuber yield, and N-uptake of the potato (*Solanum tuberosum* L.) under Tasmanian conditions. On-farm monitoring plots were established in north-west Tasmania within four different well–managed potato fields grown during the 2012/13 cropping season. Detailed soil, weather, and crop data sets measured in the on-farm plots planted with two cultivars, 'Russet Burbank' and 'Moonlight' were used to calibrate and evaluate the model. The model realistically reproduced the observed tuber yield with high accuracy (a mean N-RMSE of 15.4% and modelling efficiency of 1.0 for both cultivars). Measured tuber yields averaged 17 t ha^{-1} for 'Russet Burbank' with a simulated yield of 20 t ha^{-1}. For 'Moonlight' simulated tuber yield was 16.0 t ha^{-1} compared to measured yield of 15.1 t ha^{-1}. Whilst the data used in the study is limited to one cropping season, the simulation results have provided insight on the model

performance under Tasmanian potato growing conditions and have increased confidence in the use of model for other purposes including climate change impact studies. However, modification of some key crop specific parameters may be needed to improve the predictions of other plant organs beside the tuber.

Additional Keywords: APSIM-potato model, climate change, parameterisation, evaluation, simulation, tuber dry matter yield

Introduction

Potato (*Solanum tuberosum* L.) has a global role as the third most important food crop grown in most continents (Bradshaw & Bonierbale 2010; Birch et al. 2012; FAO 2015) yet the application of simulation models to this crop has lagged behind other major crops (White et al. 2011). In Australia, the Agricultural Production Systems sIMulator potato model (APSIM–potato model) is still in its infancy compared to other plant modules such as APSIM-wheat, maize and sorghum. For example, the list of APSIM publications was 551 as at June 30, 2014, with an upsurge from 2007 onwards (Holzworth et al. 2014) but there are very few publications on potato.

Potato is an important vegetable produced in Australia with approximately 1.3 million tons worth about 0.7 billion dollars (AU) produced in the 2012-13 cropping season (ABS 2014). South Australia, Victoria and Tasmania are the leading potato producing States. Together, they contribute over 70% of the national total tuber production (ABS 2014). In Tasmania, potato is the mainstay of the vegetable industry representing over two thirds of the industry volume (ABS 2014; AUSVEG 2014). Relatively cool weather conditions, suitable soils, high water availability and quality, and relatively pest and disease free status gives Tasmania's potato growers a comparative advantage over other Australian regions (Beattie 2010). Over

80% of the potatoes produced in Tasmania are sold to the other States and the remainder is consumed locally (DPIPWE 2014).

Potatoes are mainly cultivated in Tasmania's north-west but, with the expansion of irrigation schemes, potato production is increasingly moving to the less traditional sandy duplex soils of the Midlands and the north-east of Tasmania. The availability of quality irrigation water may not be a constraint in the near future in Tasmania because irrigation programs are expanding (DPIPWE 2015) but there is an urgent need for research to underpin potato production so that it is profitable and environmentally sustainable. Crop simulation modelling can be applied in investigative studies in a wide range of problem domains (Boote et al. 1996; Hammer et al. 2002) such as the response of potato to different climates, soil types and management options in Tasmania.

The first potato model was developed about five decades ago (Sands et al. 1979). Since then, over 30 potato crop growth models have been developed (Raymundo et al. 2014). The most significant ones include SUBSTOR-Potato, LINTUL-Potato, SOLANUM, APSIM-Potato, SPUDSIM, POMOD, SIMPOTATO, Infocrop-Potato and Potato Calculator (Raymundo et al. 2014; Saue & Kadaja 2014; Fleisher et al. 2017; Raymundo et al. 2017).

APSIM (which contains a suite of modules for different crops) is highly valued by researchers in most parts of the world (Keating et al. 2003; Holzworth et al. 2014). Products such as "Crop Arm" and "Yield Prophet" have been derived from APSIM and are decision support tools designed to meet the needs of farmers, agronomists, and consultants (Holzworth et al. 2014). These products do not include potatoes. The concept of a single platform that can collate and synthesize the massive amounts of data assimilated through precision agricultural technologies such as in-field or machine borne sensors (Rad et al. 2015) will soon be commonplace and crop growth models such as APSIM will provide the synthesis of such data to provide actionable information for farmers.

Crop growth models need to be accurately parameterised against measured data before they can be applied in new areas and for new cultivars (Boote et al. 2010; Palosuo et al. 2011; Raymundo et al. 2014). Also important in crop modelling is the need to evaluate the predictive ability of a given model for one cultivar grown across a wide range of climatic regions (Raymundo et al. 2017). While the APSIM-potato model has been tested and calibrated with a number of data sets from long-term experiment in Lincoln, New Zealand and has accurately reproduced effects of different rates of N-fertilizer, sowing dates, plant density and irrigation treatments, there are knowledge gaps that need to be addressed before the model is widely used (Brown et al. 2011). The current study sought, under Tasmanian conditions, to parameterise the APSIM-potato model with two different cultivars ('Russet Burbank' and 'Moonlight') and to evaluate model performance in simulating, in-season and end-of-season biomass, tuber yield and N-uptake of the potato. This is the first time APSIM-potato has been tested outside New Zealand.

Materials and Methods

Site description

On-farm monitoring plots were established in north-west Tasmania within well-managed potato fields grown during the 2012/13 cropping season where all the management events were carried out by the farmer and no additional treatments were introduced. There were four different on-farm monitoring plots and each plot measured 21 m long by 7.3 m wide. One plot was located at Tasmanian Institute of Agriculture Vegetable Research Facility, (TVRF) (41.01S, 146.26E, 125 AMSL), two plots at Lower Barrington, (LB1 and LB2) (41.26S, 146.30E, 229 AMSL) and (41.26S, 146.30E, 233 AMSL), and one plot at Sassafras, (SSF) (41.25S, 146.5E, 115 AMSL). All the four potato fields used for the study belonged to commercial growers contracted by Simplot Australia Ltd and the growers followed the recommended agronomic practices for production of processing potatoes as advised by a field agronomist.

At planting, soil samples down to 0.6 m depth were taken from each of the four on-farm plots in triplicate. Samples were chemically analysed using analytical techniques described in Rayment and Lyons (2011), at AgVita Analytical Laboratories, Devonport, Tasmania. Samples were analysed using the increments: 0-15, 15-30, 30-60 cm (Table 3.1).

Table 3.1 Pre-planting soil chemical properties at each of the on-farm monitoring plots in north-west Tasmania

Depth	pH-H_2O	EC	P	K	S	OC	Total N	Total C	NO_3-N	NH_4+	C/N
cm	(1:5)	dS m^{-1}		Mg kg^{-1}			%		Kg ha^{-1}		Ratio
L. Barrington 1 (LB1)											
00-15	7.0	0.08	225.0	505.9	6.5	3.9	0.3	4.4	8.4	10.1	13.2
15-30	6.9	0.08	184.0	448.9	8.8	3.5	0.3	3.9	8.7	9.7	13.0
30-60	6.5	0.11	74.0	341.8	55.9	2.5	0.2	2.9	5.6	10.0	13.7
Sassafras (SSF)											
00-15	6.8	0.19	206.0	261.0	8.6	1.9	0.8	2.1	15.4	9.1	11.7
15-30	6.8	0.09	120.0	181.6	15.1	1.5	0.1	1.7	17.7	10.6	14.3
30-60	6.8	0.09	57.3	140.1	28.8	1.1	0.1	1.3	12.6	9.9	14.6
Tasmanian Institute of Agriculture Vegetable Research Facility (TVRF)											
00-15	6.6	0.14	125.0	540.2	29.1	3.3	0.4	4.0	28.5	12.8	9.8
15-30	6.5	0.12	58.1	287.9	66.0	1.9	0.2	2.4	15.5	11.2	11.7
30-60	6.5	0.12	48.0	258.9	75.6	1.7	0.2	2.2	11.9	10.1	12.0
L. Barrington 2 (LB2)											
00-15	6.5	0.1	208.0	400.6	18.6	3.4	0.3	4.0	24.1	11.6	11.7
15-30	6.5	0.12	133.0	282.1	17.0	2.7	0.3	3.2	17.1	10.8	11.2
30-60	6.5	0.12	84.5	263.5	37.0	2.1	0.2	2.6	19.8	11.4	11.4

P: Phosphorus, K: Potassium, S: Sulphur, NO_3^- N: Nitrate nitrogen, NH_4^+: Ammonium nitrogen, EC: Electrical conductivity, N: Nitrogen, C: Carbon, OC: Organic Carbon.

Agronomic practices

Two commercial potato cultivars planted on various dates in October 2012 and managed by the growers were used for data collection: ‘Russet Burbank’ planted at SSF and LB1, and ‘Moonlight’ planted at TVRF farm and LB2. Cut tubers locally referred to as tuber ‘sets’ were used at SSF and LB sites and whole tubers were used at TVRF site. In Tasmania, large tubers of 250 to 280 g are cut into seed pieces called ‘sets’ with a target of sets weighing an average of 50 g (ranging from 35 to 85 g) each with at least one eye (Beattie 2010). Whole tubers weighing between 35 g and 80 g are occasionally used as was the case for TVRF trial site.

At planting, N: P: K fertilizer (09:15:13) at a rate of 1850 kg ha^{-1} was band placed at LB1. Additional nitrogen was applied as urea at rates of 125, 71, and 142 kg N ha^{-1} at 57, 69 and 86 days after planting (DAP). Nitro Humus 323™ fertilizer was applied with irrigation water at 74, 87, 102, 111, and 123 DAP at a rate of 10 kg N ha^{-1}. At SSF, N: P: K: S fertilizer (09:14:6: S) at a rate of 1600 kg ha^{-1} was applied at planting. In-season fertilization was applied with N:K:S (23:0:25:S) at a rate of 200 kg ha^{-1} each at 53 and 70 DAP and urea at a rate of 46 kg N ha^{-1} at 88 and 87 DAP. For the on-farm monitoring plots planted with ‘Moonlight’ (i.e. at TVRF and LB2), a pre-sowing blend of nutrient mixture containing N, K, and S nutrients were pre-spread 10 days before planting at a rate of 747 kg ha^{-1}. An additional 859 kg ha^{-1} of nutrient mixture containing N, P, K, Ca, and S were band placed at planting.

Weeds, pests and diseases were controlled through frequent application of herbicides, pesticides and fungicides. At site LB1 and SSF, 294 mm and 407 mm of water was applied with center pivot irrigation system during the growing season. At both TVRF and LB2, 276 mm of water was applied using travelling gun irrigation systems. Throughout the growing season, the crops appeared in good condition and no visual disease symptoms or pest infestation was observed within the on-farm monitoring plots. Water stress was however, visually noticeable between 50 and 70 DAP at the LB2 site but not in the other three on-farm monitoring plots.

Weather data

Daily weather data used to run the simulations were obtained from SILO meteorological database (http://www.longpaddock.qld.gov.au/silo/). Daily maximum temperature (Tmax) and minimum temperature (Tmin), and rainfall for each of the four on-farm monitoring plots during the cropping season are presented in Fig.3.1 and the averages in Table 3.2. The difference in daily temperature and solar radiation between the four sites was minimal with an average Tmax, Tmin and solar radiation of 20.8±3.2 °C, 10.5± 3.5 °C and 21.6±5.5 $MJ^{-2}day^{-1}$ respectively across the on-farm plots. Total in-crop rainfall received was 285 mm at TVRF, 228 mm at LB1, 317 mm at LB2 and 204 mm at SSF. The lowest and the highest temperature across the sites were 2 °C and 31 °C. With a Tbase temperature of 2 °C (Brown et al.,2011) accumulated growing day degrees (GDD, °Cd) during the growing season ranged from 2004 to 2164 °Cd (Table 3.2). GDD are calculated from daily temperature data by taking the mean value of the daily maximum and minimum temperatures and subtracting Tbase (Mix et al. 2010).

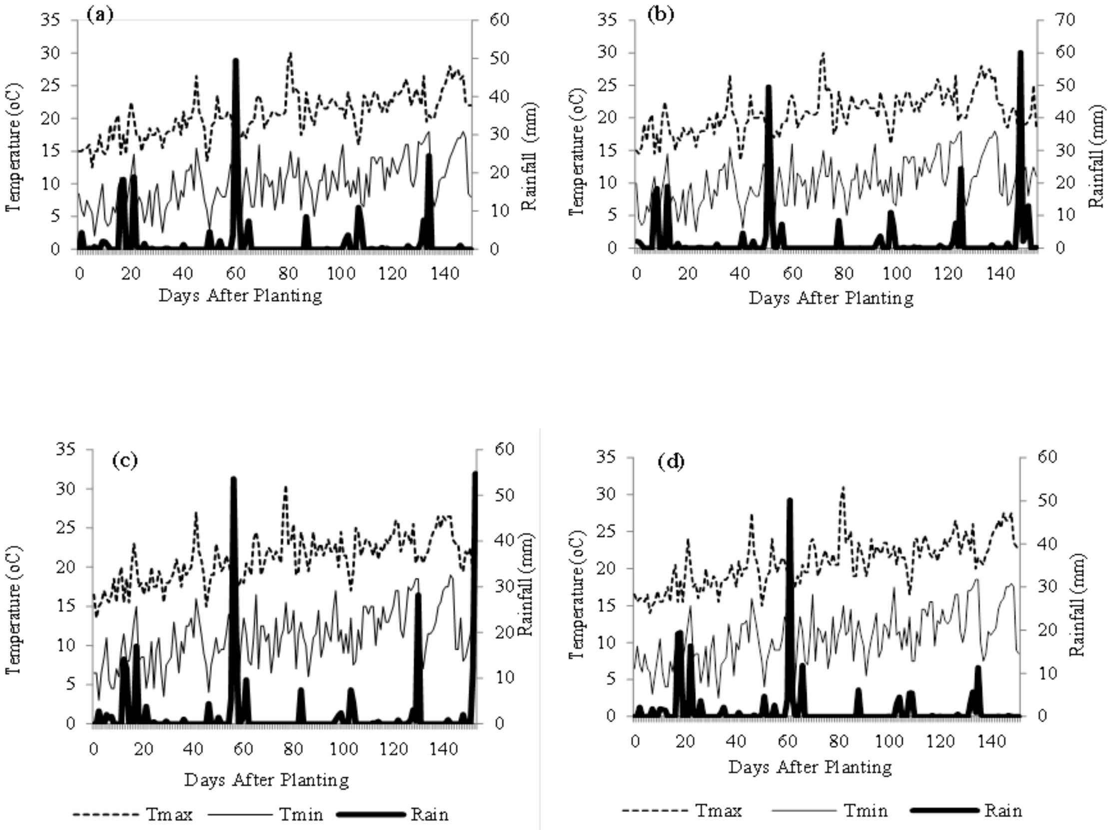

Figure 3.1 Daily maximum and minimum temperature and rainfall during the 2012-13 growing season at each of the on farm monitoring plots: LB1 (a), LB2 (b) TVRF (c) and Sassafras (d).

Table 3.2 Weather data (temperature, solar radiation, rainfall) from planting to harvesting date at each of the on-farm monitoring plots in north-west Tasmania

Data	**Units**	**TVRF**	**LB1**	**LB2**	**SSF**
Mean Tmax	°C	21±3.0	20.6±3.4	20.8±3.1	20.9±3.2
Mean Tmin	°C	11.1±3.5	10±3.6	10.3±3.4	10.7±3.6
Highest temp.	°C	30.5	30	30	31
Lowest temp.	°C	2	2	2.5	2.5
Accumulated growing day degrees at final harvest	°Cd	2164	2004	2099	2098
Mean radiation	$MJ^{-2}day^{-1}$	21.6±5.6	21.6±5.5	21.2±5.7	21.9±5.5
Total rainfall	mm	285.1	227.9	317.2	203.9

LB: Lower Barrington site 1 and 2, SSF: Sassafras, TVRF: Tasmanian Institute of Agriculture Vegetable Research Facility, Tmax: maximum daily temperature, Tmin: minimum daily temperature.

Measurements of field data

Crop measurements

Crop data were collected on a weekly basis starting at 50% tuber emergence (EM). EM was measured by counting the number of emerged plants in each on-farm monitoring plot and was assumed to have taken place when 50% of the plants had emerged from the soil surface. For each sequential harvesting, 2 adjacent plants were harvested from 6 locations within the on-farm plot, giving a total of 12 plants per plot. Growth and development parameters including the height of the main stem (MS), number of MS, number of tubers per plant and the number of leaves appearing on each MS for each sampled plant were recorded immediately after each sequential harvesting before the plants were separated into leaves (L, the whole compound leaf including petioles), stems (S) which included below and aboveground stems and tubers (T). Roots and stolons were discarded because they are not economically important, difficult to measure, and are a minor component of biomass.

Fresh weights of each of the 12 harvested plants separated into the three components (L, S and T) were recorded before a sub-sample of each organ was taken for nitrogen analysis. The dry weight of each component was determined by oven drying the sub-samples at 90 °C to a constant weight for at least 48 hours. Where samples were too bulky, a sub-sample of ca. 200 g per organ was taken for drying. Tubers were washed and diced before drying. Samples for N-Analysis were oven dried at 60 °C for 48 hours. Total nitrogen in each plant organ was determined by the Dumas high-temperature combustion method (Rayment and Lyons 2011). Although the model used in this study (APSIM-Potato) does not have a tuber distribution function, tubers were sorted into industry tuber standard categories, <75 g, 75-250 g, 250-850 g and >850 for 'Russet Burbank' and <80 g, 80-250 g and >250 g for 'Moonlight' during the final harvest.

Leaf area index (LAI) was measured on a fortnightly basis using SunScan (SS1, AT Delta-T Devices Ltd, UK), starting from the EM date. To minimise the effect of solar Zenith angle, LAI measurements were taken at around noon. For each sampling date, 12 measurements were taken per on-farm plot, in which six of the measurements were centred over rows and the other six measurements were centred over furrows. The measurements over the rows and furrows were taken alternately. All the measurements were averaged to obtain a single LAI value per on-farm plot for each sampling date.

Bulk density and Soil hydraulic properties

After harvesting, freshly-dug soil pits were used to describe and characterise the soils at each on-farm monitoring plot. Depending on the soil horizon at each site, samples were collected at 0.15 to 0.3 m intervals from soil surface down to 1.2 m. Soil cores used for determination of bulk density (BD) were collected using rings with a height of 50 mm and 74 mm internal diameter, with cores taken in triplicate down the soil profile. Soil cores were oven dried at 105 °C to a constant weight for at least 48 hours. BD expressed in g cm^{-3} is the ratio of dry soil mass to the total volume of dry soils (Cresswell & Harmilton 2002) (Table 3.3).

Soil cores for determination of soil water properties: plant available water content at saturation (SAT), drained upper limit (DUL) and crop lower limit (LL15) were collected using rings with a height of 20 mm and 48 mm internal diameter taken in triplicate down the soil profile. The rings were hammered horizontally into the profile and carefully trimmed both at the top and bottom. A 1600 Pressure Plate Extractor 5 bar (Soil Moisture Equipment Corporation, USA) was used to determine SAT, DUL and LL15 equilibrated at specified matric potential: 0 kPa for SAT, -10 kPa for DUL and -1500 kPa for LL15 (Table 3.3).

Although rooting depth was not one of the parameters measured, the presence of roots in the soil profile was visually assessed in the freshly dug pits. The pits were excavated in such a way that two opposite walls cut through the centre of the ridge and the other two walls cut through the furrow making it easy to identify potato roots from the ones existing from previous crops. Most of the roots for 'Russet Burbank' were concentrated on the upper 0.3 m depth but roots for 'Moonlight' were noticeable down to 0.9 m soil depth.

In APSIM, potential crop water uptake is simulated via relationships with root exploration factor (XL) and potential water extraction coefficient (KL), which depends on soil and crop factors. Based on the soil properties (Table 3.3), potato XF was set at a value of 1 for all the soil layers down to a maximum depth of 90 cm based on the assumption that the rooting capability between soil layers was not restricted. KL values were adjusted based on the fact that approximately 85% of potato roots are concentrated in the upper 30 cm soil layer (Vos & Groenwold 1986; Opena & Porter 1999), although roots can be found down to 1 m depending on the cultivar and soil type. Thus for the upper soil layers (0-30 cm) with high root length densities a KL value of 0.1 was used. Since root length densities are low at soil depth below 30 cm, KL value was reduced to 0.06 for depths ranging between 30 cm and 60 cm and to 0.03 for depths between 60 and 90 cm. A KL value of 0.02 was set for soil depth below 90 cm.

Table 3.3 Measured soil bulk density and hydraulic properties down to 1.2 m soil depth for each of the on-farm monitoring plots used as input parameter data to run the simulations.

Depth (cm)	**BD** (g cm^{-3})	**Air dry**	**LL15** (mm mm^{-1})	**DUL**	**SAT**
TVRF					
00-15	1.29	0.30	0.31	0.46	0.52
15-27	1.21	0.33	0.33	0.46	0.51
27-60	1.17	0.24	0.23	0.47	0.53
60-97	1.19	0.38	0.38	0.51	0.52
97-120	1.20	0.41	0.41	0.46	0.52
L. Barrington 1					
00-15	1.18	0.30	0.37	0.46	0.58
15-30	1.21	0.37	0.37	0.49	0.51
30-50	1.23	0.40	0.40	0.49	0.52
50-82	1.20	0.39	0.39	0.49	0.52
82-120	1.15	0.36	0.36	0.49	0.57
L. Barrington 2					
00-15	1.07	0.20	0.25	0.40	0.51
15-30	1.17	0.28	0.28	0.43	0.51
30-66	1.17	0.36	0.36	0.47	0.53
66-90	1.17	0.38	0.38	0.49	0.56
90-120	1.17	0.37	0.37	0.53	0.56
Sassafras					
00-14	1.45	0.10	0.18	0.34	0.42
14-28	1.43	0.19	0.19	0.33	0.39
28-43	1.47	0.26	0.26	0.41	0.42
43-79	1.42	0.27	0.27	0.41	0.43
79-120	1.26	0.29	0.29	0.46	0.49

BD: bulk density, LL15: crop lower limit, DUL: drained upper Limit, SAT: saturated water content

Model parameterization and evaluation

*The Model:*This study used APSIM-potato (version 7.5), a new plant model built in the Plant Modelling Framework (Brown et al. 2014) and described in detail by Brown et al. (2011). In brief, APSIM-potato is a comprehensive daily time-step, deterministic crop model that integrates with the APSIM soil, SOILN, management, and user interface components to provide robust and user friendly simulation.

The model predicts biomass, tuber yield, N-uptake, water use efficiency of the potato plant, soil water variables and other plant parameters on a daily basis in response to inputs of daily weather data, soil characteristics, crop parameters and management events. It uses a constant RUE (Radiation Use Efficiency) value of 1.2 g dry matter MJ^{-I} of intercepted radiation. The water stress factor (f_w) is optimum at 1.0 when the crops are supplied with adequate water and will decline to zero when the soil moisture is nearing the crop lower limit (LL15). At daily average temperatures of 2 °C (Tbase), the temperature stress factor (ft) values rises from zero to a maximum value of 1.0 at daily mean temperatures of between 12 °C and 24 °C. Above 24 °C, the ft values declines to zero at 34 °C.

Using inputs of tuber planting density and the number of main stems per tuber, the model calculates the population density of primary stem units which in turn are used to predict the rate of appearance, expansion, size and duration of individual leaves on the primary stems and the occurrence of branching. APSIM-potato partitions dry matter assimilates into four state variables; leaf, stem, root and tuber.

Model parameterization

The experiments described above were simulated using APSIM-potato with the measured weather, soil and crop data, and management events. Daily weather data (global solar radiation, rainfall, maximum and minimum temperatures) used in the simulations are presented in Fig.3.1. Soil chemical properties: initial organic carbon content (OC), Nitrate nitrogen (NO_3^-N), Ammonium nitrogen (NH_4^+), $pH_{(H2O)}$, and electrical conductivity (EC) (Table 3.1) : and soil hydraulic properties including SAT, DUL, CLL, and air dry and bulk density (Table 3.3) were used as input data to run the simulations. Initial soil water content was set at 50% filled from the top. Crop data and management events used to initialize the model are summarized in Table 3.4.

Table 3.4 Management events at each of the on-farm plots used as input parameter data to run the simulations

Site events	**TVRF**	**LB1**	**LB2**	**SSF**
Planting date	20/10/2012	16/10/2012	25/10/2012	15/10/2012
Emergence date	13/11/2012	17/11/2012	17/11/2012	13/11/2012
Sowing depth (mm)	175	150	175	150
Row spacing (mm)	810	810	810	810
Inter-row spacing (mm)	250	300	250	300
Plant density (plants m^{-2})	4.9	4.1	4.9	4.1
No.of MS $plant^{-1}$	4.6	2.0	4.1	2.0
Stem density(stems m^{-2})	22.8	8.2	20.2	8.0
N-application (kg N ha^{-1})	95.6	338.2	95.6	328.0
Total irrigation water applied (mm)	276.3	294.2	275.5	406.6
Final harvesting date	22/03/2013	15/03/2013	28/03/2013	15/03/2013
Duration of growing season (days)	153	150	154	151

LB: Lower Barrington site 1 and 2, SSF: Sassafras, TVRF: Tasmanian Institute of Agriculture Vegetable Research Facility, MS: main stem.

Crop growth models require parameterization of the default crop parameters before the models are applied in confidence with new cultivars (Palosuo et al. 2011). In each of the APSIM crop models, there are two major parts: the crop-specific constants and cultivar-specific parameters (Keating et al. 2003). The cultivar-specific parameters can be ‘overridden’ where a cultivar is distinctly different from the model base cultivar (which is ‘Russet Burbank’ in the case of APSIM-potato). ‘Moonlight’ is a medium maturity cultivar in which tuber initiation and bulking occurs over a relative short period of time (Anderson et al. 2004) and ‘Russet Burbank’ is late maturing, and tuber initiation and canopy development takes place over relatively longer period (Beattie 2010). Additionally, ‘Moonlight’ is determinate with haulms that stop producing leaves after flowering, giving shorter stems that tend to grow upright. 'Russet Burbank' is indeterminate and continues to produce leaves after flowering, producing longer stems which tend to become prostrate. Thus for 'Moonlight', we first parameterised the model by changing key cultivar-specific parameters as the cultivar is distinctively different from 'Russet Burbank'. Measured data for 'Moonlight' were grouped into data that were used to set up the model (number of main stem plant^{-1}, number of leaves MS^{-1}) and the data used to evaluate the model (aboveground biomass, tuber yield, N-uptake, LAI).

Parameterization for 'Moonlight' was step-wise, adjusting one parameter at a time. The changes were guided by field observations of the phenology, leaf duration, final number of leaves on the main stem and LAI relative to the observation for 'Russet Burbank'. Also, it was guided by published descriptors of 'Moonlight' (Anderson et al. 2004). We adjusted four dominant cultivar specific parameters: the leaf lag duration, final number of leaves per main stem, branching rate and leaf maximum area. The other cultivar-specific parameters were assumed to be equal to the values for 'Russet Burbank' and were left unchanged. All crop-specific constants were unchanged. No changes were made for both crop-specific constants and cultivar specific parameters for 'Russet Burbank'.

Model evaluation

The parameterized APSIM-potato was used to run the simulations and the performance of the model was assessed by comparing simulated crop data with measured crop data. Measured leaf and stem biomass, tuber dry matter yield, leaf area index (LAI), and plant nitrogen uptake per organ were compared with the simulated data at a given date of sampling. All comparisons were on a dry weight basis for tuber yield and aboveground biomass (leaf and stem).

Model evaluation statistics

The model reliability in predicting potato biomass, and tuber yield was evaluated using Root Mean Squared Error (RMSE) an error index statistic expressed as percentage that gives a measure of the relative difference of simulated verses observed data (Soler et al. 2007), and the Willmott d index of modelling efficiency (EF), a dimensionless statistical value that provides an assessment of model performance (Krause et al. 2005; Moriasi et al. 2007; Adiku et al. 2011). RMSE (Eq.1) was normalised using the mean of observed values (Soler et al. 2007). Normalized RMSE (N-RMSE) gives a measure (%) of the relative difference of simulated versus observed data. The agreement between the simulated and the observed data is considered excellent if the N-RMSE value is less than 10%, a value of 10 to 20% is considered good, a value of 20 to 30% is viewed as fair while the agreement is considered poor if the N-RMSE value is greater than 30% (Soler et al. 2007). An EF (Eq.2) value of 1.0 is considered excellent, values ranging from 0.0 to >1.0 are considered acceptable and the level of performance is considered poor if the values are less or equal to zero (Loague & Green 1991; Moriasi et al. 2007). RMSE and EF are often used in model performance evaluation including in previous potato modelling studies (Tubiello et al. 2002; Condori et al. 2010; Carli et al. 2014).

$$N - RMSE = \sqrt{\frac{\sum_{i=1}^{n}(S_i - O_i)^2}{n}}\ x\ \frac{100}{M} \qquad (1)$$

$$EF = 1 - \frac{\sum_{i=1}^{n}(O_i - S_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2} \qquad (2)$$

Where n is the number of observations, S_i refers to the simulated value, O_i refers to the observed value and M is the mean of the observed values.

Results

Crop performance at the on-farm monitoring plots

There was little variation in the weather conditions (Table 3.2) during the growing seasons across the trial sites or in the cultural practices by cultivar (e.g. nitrogen application and irrigation water supply, Table 3.4). All the sites recorded high emergence rate with an average of 98.2% for ‘Moonlight’ and 89.5% for ‘Russet Burbank’. This is an indication that the seed tuber sets used by the growers were of high biological (level of tuber-borne disease infection and physiological age) and commercial (uniformity and size of tubers and external defects) quality.

Leaf area index, ($m^2\,m^{-2}$) values were higher for ‘Russet Burbank’ compared to ‘Moonlight’ in both trial sites. The maximum LAI (LAI-max) for ‘Russet Burbank’ was 6.9 $m^2\,m^{-2}$ at 109 DAP at Sassafras (SSF) and 5.8 $m^2\,m^{-2}$ at 94 DAP at Lower Barrington (LB1). ‘Moonlight’ had lower LAI-max, 3.2 $m^2\,m^{-2}$ at 97 DAP at Tasmanian Institute of Agriculture Vegetable Research Facility (TVRF), and 3.7 $m^2\,m^{-2}$ at 99 DAP at Lower Barrington (LB2). The end-of-season tuber yield averaged 73.5 t FW ha^{-1} (fresh weight) across the cultivars. Tuber yield for ‘Russet Burbank’ was 75.0 t $FWha^{-1}$ at LB1 and 80.7 t $FWha^{-1}$ at SSF while 74.2 (TVRF) and 64.1 t $FWha^{-1}$ (LB2) were obtained for ‘Moonlight’. Tuber yield in Tasmania ranges from 48 to 75 t $FWha^{-1}$ (Phil. Pers. Comm. 2013) with an average tuber yield of 48.5 t $FWha^{-1}$ for the period 2003 to 2013 (ABS 2014). The higher tuber yield at Sassafras for ‘Russet Burbank’ was to a larger extent, due to higher tuber weight compared to the crop grown at LB1 (Fig.3.2) which had higher number of tubers $plant^{-1}$. The opposite was true for ‘Moonlight’ with the crop grown at TVRF registering higher yield mainly as a result of higher number of tubers $plant^{-1}$. The average tuber dry matter (DM) content was 21.9% a cross cultivars and trial sites.

Evaluation of model simulation

Number of leaves per main stem (MS)

As shown on Fig.3.3, the simulated rate of leaf appearance was faster than the observed rate and subsequently the simulated final number of leaves appearing on each main stem was higher than the number observed throughout the growing season for both cultivars across the sites. The index of agreement was good with N-RMSE values of 27.5% for ‘Russet Burbank’ at LB1 and 16.4% at SSF and for ‘Moonlight’ the values were 15.4% at TVRF and 15.8% at LB2 (Table 3.5 and 3.6). Modelling efficiency (EF) was good especially for ‘Moonlight’ averaging 0.7 for both sites and 0.4 for ‘Russet Burbank’.

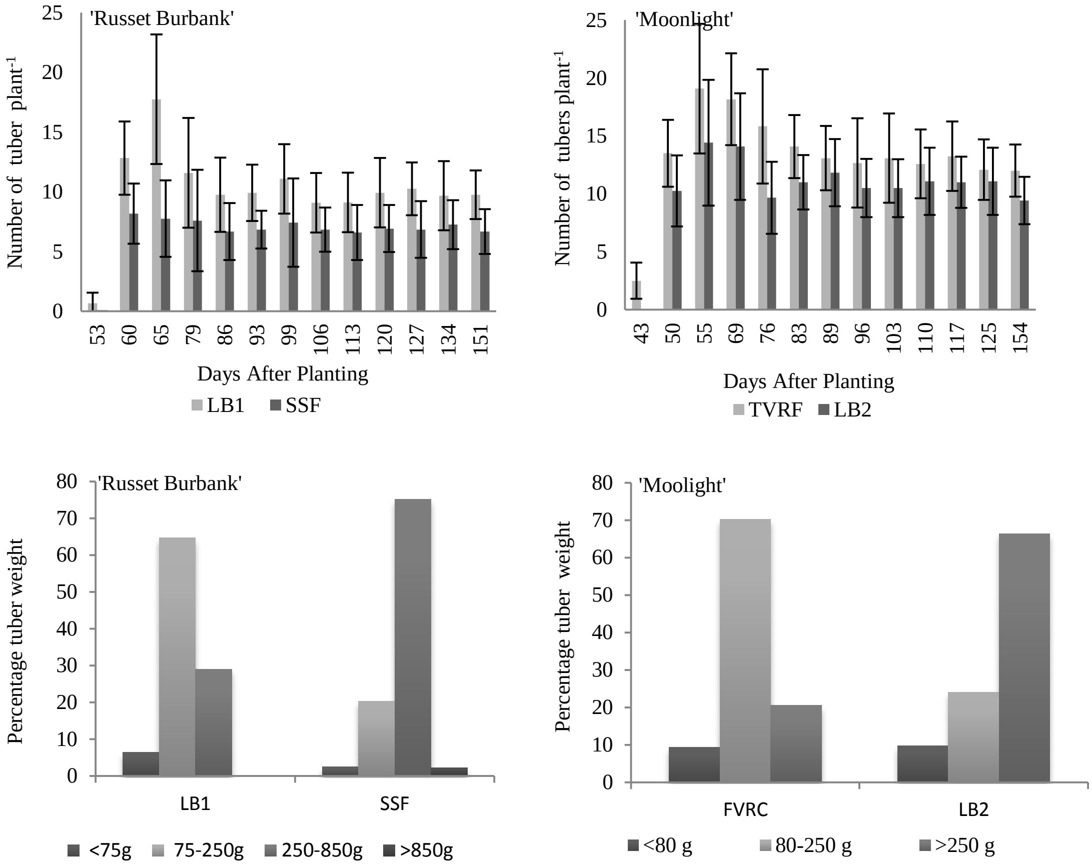

Figure 3.2 Average number of tubers plant^{-1} and the proportion (%) of the total tuber yield by tuber size category as per the industry standard for ‘Russet Burbank’ and ‘Moonlight’ during the final harvest at each of the four sites: Lower Barrington (LB1 ad LB2), Tasmanian Institute of Agriculture Vegetable Research Facility (TVRF) and Sassafras (SSF). The bars in the top graphs represent the standard deviation (n =12).

Aboveground biomass

Graphically, simulated values were close or equal to the observed values during the vegetative and early tuber growth stage (up to 80 DAP for both cultivars) for both leaf and stem dry biomass (Fig 3.4). However, the measured maximum leaf and stem biomass were higher than the simulated values. Also, the simulated rate of leaf senescence after reaching the peak was faster and this gave lower values of simulated leaf dry biomass in the second half of the growth cycle. N-RMSE values for ‘Russet Burbank’ (Table 3.5) grown at LB1 were 25.2% for leaf and 25.4% for stem, 36.9% for leaf and 29.8% for stem at SSF. Compared to ‘Russet Burbank’, the index of agreement was poorer for ‘Moonlight’ with N-RMSE values of 40.9% for leaf and 41.7% for stem at TVRF, 44.9% for leaf and 32.7% for stem for the crop grown at LB2 (Table 3.6).

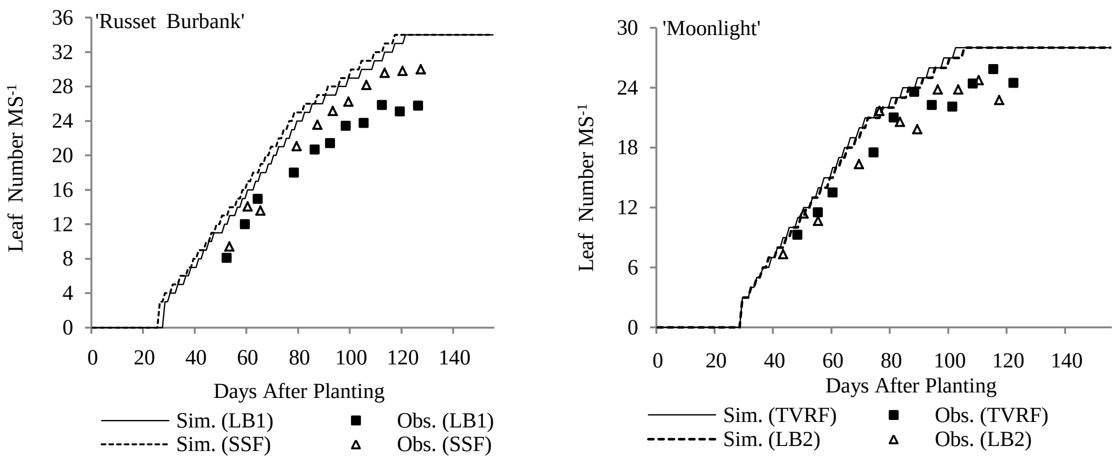

Figure 3.3 Change in observed and simulated number of leaves appearing on each main stem (MS) over time for ‘Russet Burbank’ grown at LB1 and SSF and ‘Moonlight’ grown at TVRF and LB2

Table 3.5 Statistical comparison between observed and simulated data for 'Russet Burbank' grown at Lower Barrington (LB1) and at Sassafras (SSF)

Crop data	Units	RMSE		N-RMSE (%)		EF	
		LB1	SSF	LB1	SSF	LB1	SSF
Tuber DM yield	t ha^{-1}	1.2	1.7	13.1	19.5	1.0	0.9
Stem dry biomass	t ha^{-1}	0.3	0.4	25.4	29.8	0.7	0.6
Leaf dry biomass	t ha^{-1}	0.4	0.7	25.2	36.9	0.7	0.4
Aboveground dry biomass	t ha^{-1}	1.0	1.0	36.1	33.6	0.3	0.5
LAI	m^2 m^{-2}	0.9	1.5	25.4	35.1	0.8	0.3
Tuber N uptake	kg N ha^{-1}	25.3	27.0	20.6	21.1	0.9	0.9
Stem N uptake	kg N ha^{-1}	5.3	20.5	22.1	59.5	0.6	-0.3
Leaf N uptake	kg N ha^{-1}	16.5	39.5	20.7	40.4	0.8	0.3
No. LMS	No.	5.5	3.7	27.5	16.4	0.1	0.7
Plant height	cm	10.7	16.1	18.1	24.7	0.8	0.7

RMSE: Root mean square error, N-RMSE: Normalized root mean square error, EF: Modelling Efficiency, DM: dry matter, N: Nitrogen, LMS: number of leaves on each main stems (MS).

Table 3.6 Statistical comparison between observed and simulated data for 'Moonlight' grown at Lower Barrington (LB2) and at Tasmanian Institute of Agriculture Vegetable Research Facility (TVRF) trial sites

Crop data	Units	RMSE		N-RMSE (%)		EF	
		TVRF	LB2	TVRF	LB2	TVRF	LB2
Tuber DM yield	t ha^{-1}	1.2	1.2	12.7	16.3	1.0	1.0
Stem dry biomass	t ha^{-1}	0.6	0.4	41.7	32.7	0.0	0.6
Leaf dry biomass	t ha^{-1}	0.6	0.5	40.9	44.9	-0.7	-0.5
Above ground dry biomass	t ha^{-1}	0.8	0.5	27.8	21.7	0.4	0.7
LAI	m^2 m^{-2}	0.9	1.2	36.9	48.0	-0.2	-2.7
Tuber N uptake	kg N ha^{-1}	32.6	29.0	28.5	36.8	0.8	0.7
Stem N uptake	kg N ha^{-1}	10.3	8.4	46.8	49.6	-2.3	-0.5
Leaf N uptake	kg N ha^{-1}	10.1	12.7	17.1	24.4	0.5	0.5
No. LMS	No.	3.0	3.1	15.4	15.8	0.7	0.7
Plant height	cm	13.0	12.6	21.5	24.8	0.7	0.6

RMSE: Root mean square error, N-RMSE: Normalized root mean square error, EF: Modelling Efficiency, DM: dry matter, N: Nitrogen, LMS: number of leaves on each main stems (MS).

The prediction varied per location with the best agreement (N-RMSE <30%) between simulated and observed leaf and stem biomass being that of 'Russet Burbank' at LB1. The EF values, an average of 0.6 for leaf and 0.7 for stem for ‘Russet Burbank’ implies that model performance was within acceptable range for both leaf and stem dry matter. In contrast, low EF values for ‘Moonlight’, an average of -0.6 for leaf and 0.3 for stem indicates poor simulation results.

Leaf area index

Simulated LAI values (Fig. 3.5) fitted well with the observed values both for ‘Russet Burbank’ and ‘Moonlight’ during the vegetative and early tuber growth stage, (up to 60 DAP for ‘Moonlight’ and 80 DAP for ‘Russet Burbank’). However, there was large deviation afterwards with measured maximum LAI being higher than the simulated values for ‘Russet Burbank’ and lower for ‘Moonlight’. Similarly, there was deviation in the decline of LAI values after reaching the peak with simulated values declining faster than observed for both cultivars. N-RMSE values for ‘Russet Burbank’ at LB1 was 25.4% and 35.1% at SSF and for ‘Moonlight’ the values were 36.9% at TVRF and 48.0% at LB2 (Table 3.5 and 3.6). Notably, the simulation followed a similar trend as that of leaf biomass with the best index of agreement (N-RMSE of <30%) between simulated and observed LAI being that for ‘Russet Burbank’ at LB1.

Compared to LB1, the crop at SSF produced excessive growth of haulms and hence high LAI possibly as a result of high number of irrigation events (data not shown) and high amount irrigation water (Table 3.4) supplied coupled with high nitrogen application. The excessive growth of haulms was not fully captured by the model. Across the sites, a high N-RMSE (>30%) values for ‘Moonlight’ indicates unsatisfactory index of agreement between the simulated and observed LAI. Also, low EF values, -0.2 for ‘Moonlight’ at TVRF and -2.7 at B2 is an indication of poor model performance in simulating LAI for the cultivar. Although the crop at TVRF and LB2 received equal amount of rainfall (Table 3.4), a water stressed period where no irrigation was applied and little rainfall was received between 50 and 70 DAP at LB2 resulted in a decline in observed LAI values but the crop recovered after irrigation was applied. The water stressed period which was noticeable in the field was not captured by the model.

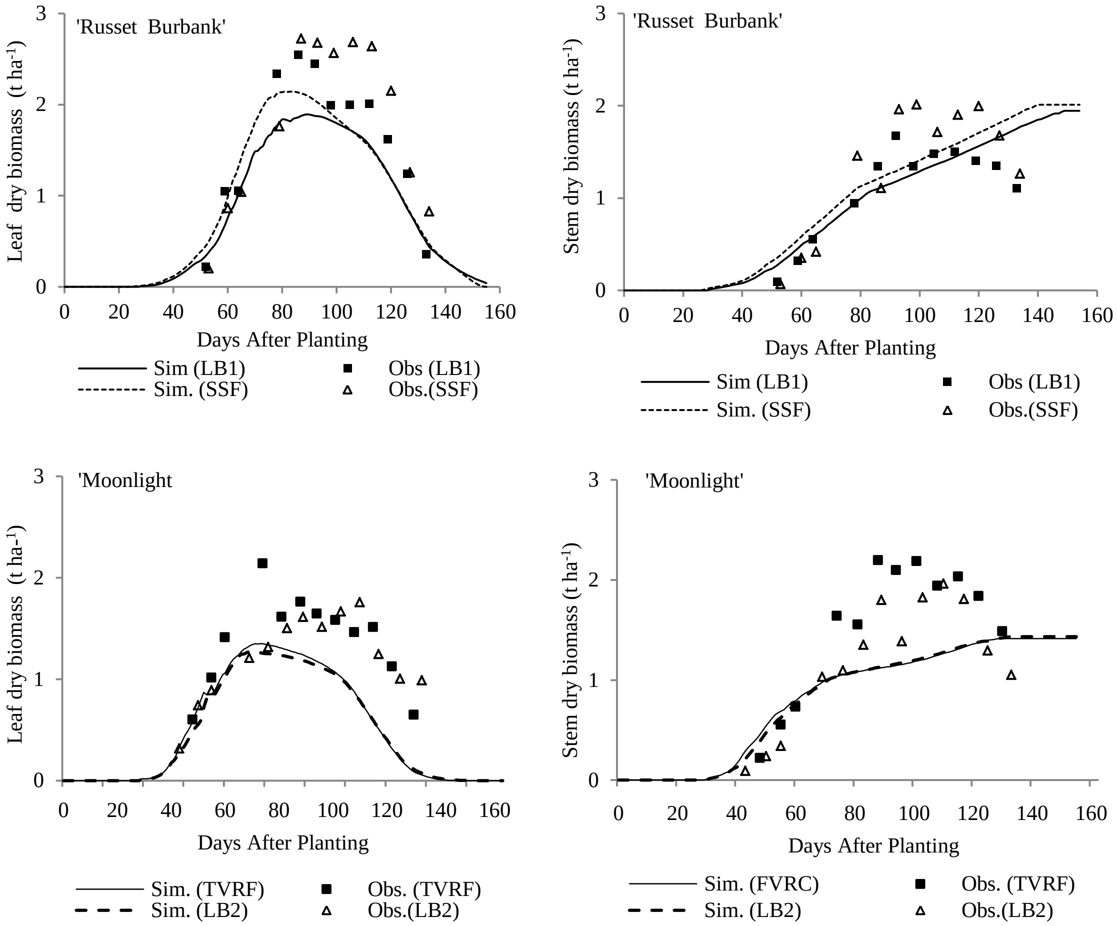

Figure 3.4 Change in observed and simulated stem and leaf biomass dry weight (t ha^{-1}) over time for ‘Russet Burbank’ grown at LB1 and SSF and ‘Moonlight’ grown at LB2 and TVRF.

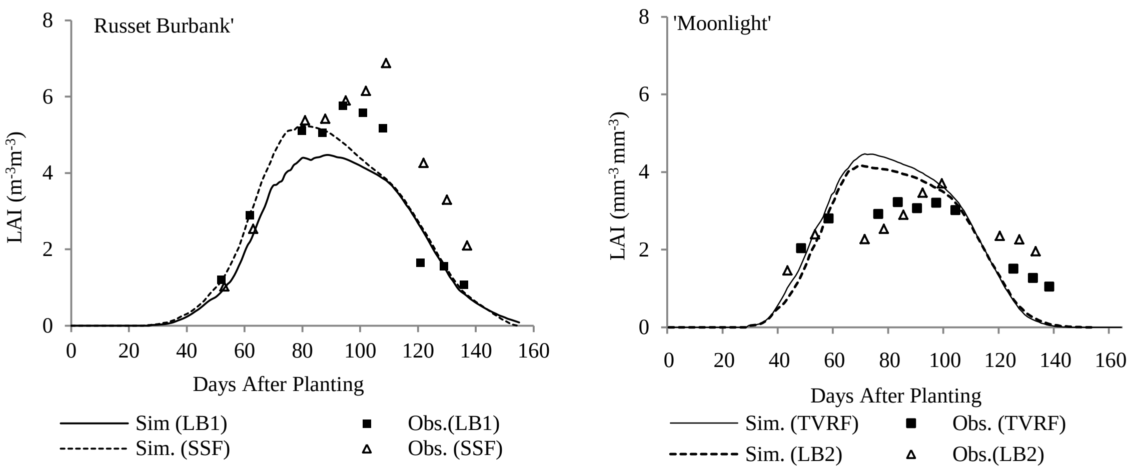

Figure 3.5 Change in observed and simulated leaf area index (LAI) over time for 'Russet Burbank' grown at LB1 and SSF and 'Moonlight' grown at TVRF and LB2.

Tuber yield

The agreement between the simulated and the observed tuber dry matter yield was good for both cultivars and across localities (Fig.3.6). N-RMSE values for 'Russet Burbank' grown at LB1 was 13.1% and 19.5% at SSF and for Moonlight' N-RMSE values we 12.7% at TVRF and 16.3% at LB2 (Table 3.5 and 3.6). The low N-RMSE values of less than 20% for all the sites is an indication of good accuracy of the APSIM-potato model to predict tuber yield. Also, the high EF values, an average of 1.0 for both cultivars imply an excellent level of model performance. Graphically, the simulated values fitted well with observed data except at the latter growth stages when the simulated values were higher for 'Russet Burbank' in both sites and for 'Moonlight' at LB2 (Fig.3.6).

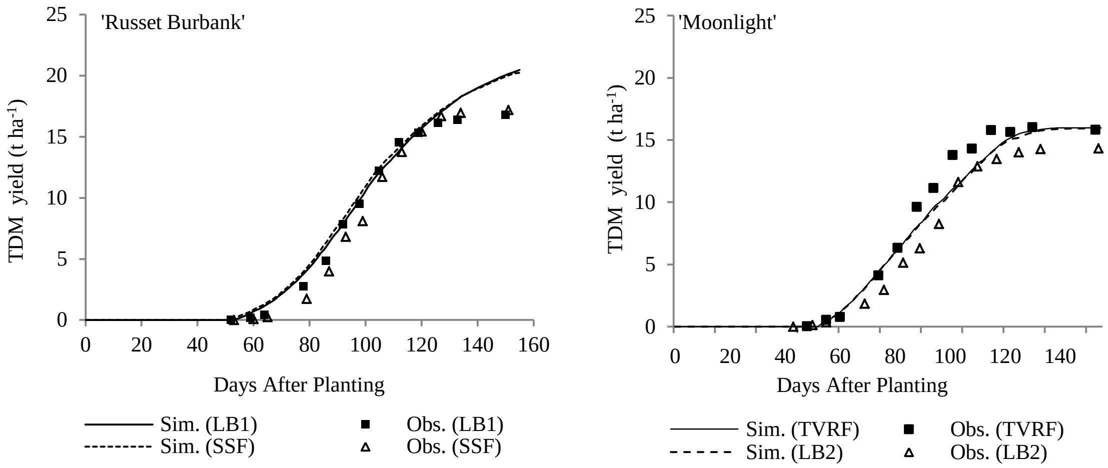

Figure 3.6 Change in observed and simulated tuber dry matter yield (t ha^{-1}) over time for 'Russet Burbank' grown at LB1 and SSF and 'Moonlight' grown at TVRF and LB2.

Plant nitrogen uptake per organ

Tuber total nitrogen uptake produced an overall good agreement between the simulated and observed values. N-RMSE values were 20.6% for 'Russet Burbank' at LB1 and 21.1% at SFF and for 'Moonlight' the values were 28.5% at TVRF and 36.8% at LB1 (Table 3.5 and 3.6). A high EF value, an average of 0.9 for 'Russet Burbank' and 0.7 for 'Moonlight' shows an excellent performance of the model in simulating tuber nitrogen uptake. Graphically, comparison of simulated values with observed values followed similar pattern although the model was biased towards over-estimation of tuber nitrogen uptake for 'Russet Burbank' at both on-farm plots and 'Moonlight' at LB2. At TVRF, simulated tuber nitrogen values were much lower than the observed values (Fig.3.7).

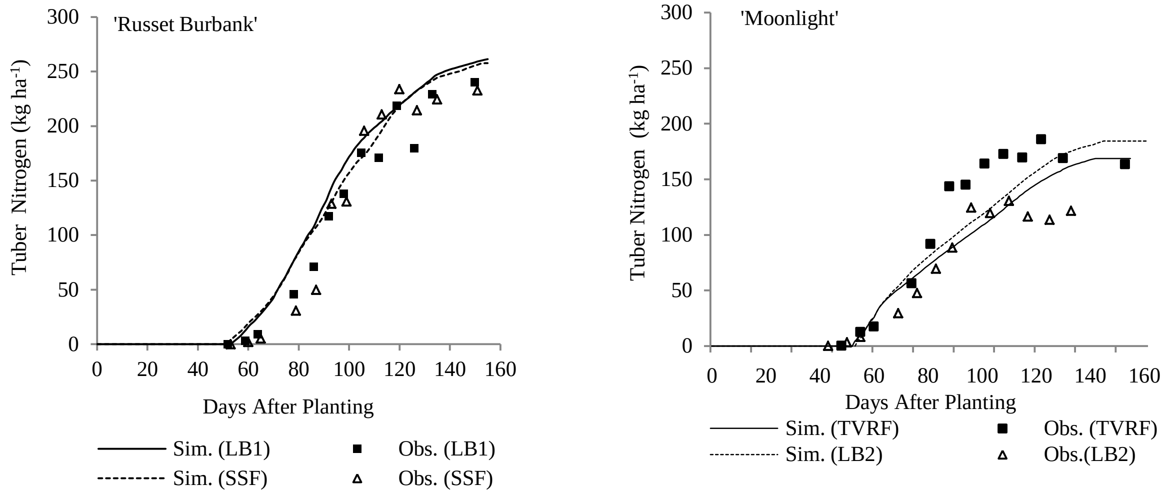

Figure 3.7 Change in observed and simulated total tuber nitrogen uptake over time for ‘Russet Burbank’ grown at SSF and LB1 and ‘Moonlight’ at TVRF and LB2.

There was variation in the simulation results for leaf and stem nitrogen uptake for both cultivars (Fig.3.8). For ‘Moonlight’, the index of agreement was good for leaf nitrogen uptake for both on-farm plots (N-RMSE of 17.1% at FRVC and 24.4% at LB2) but poor for stem nitrogen uptake at both sites (N-RMSE > 30). For ‘Russet Burbank’, the agreement at LB1 was good for leaf and stem nitrogen uptake with N-RMSE values of 20.7% for leaf and 22.1% for stem. The model performance was within acceptable levels with EF values of 0.8 (leaf) and 0.6 (stem) for ‘Russet Burbank’ at LB1. However, the model performance was poor for both leaf and stem nitrogen uptake with low EF values of 0.3 (leaf) and -0.3 (stem) for ‘Russet Burbank’ at SSF. Also the EF for stem nitrogen uptake was poor for ‘Moonlight’ at both sites with values of -2.3 at TVRF and -0.5 at LB1 (Table 3.5 and 3.6).

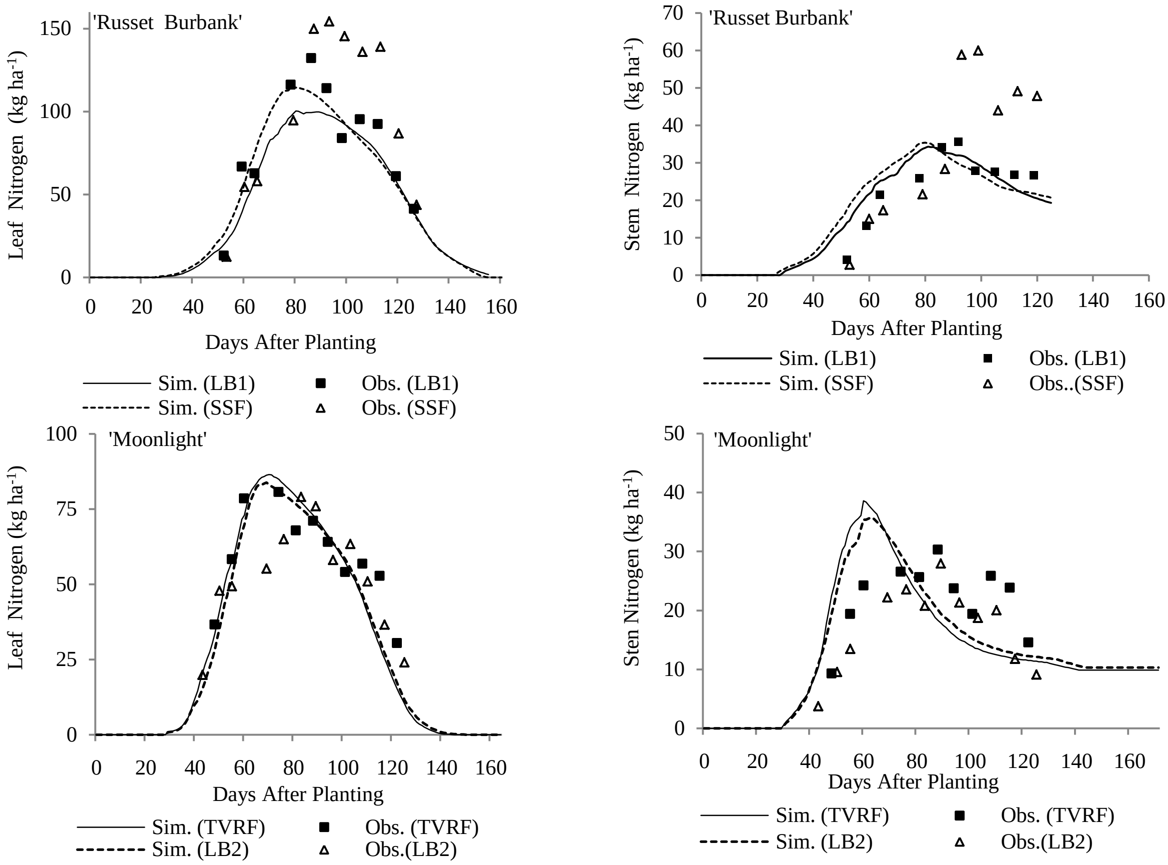

Figure 3.8 Change in observed and simulated aboveground biomass nitrogen uptake (stem and leaf dry weight) over time for ‘Russet Burbank’ grown at SSF and LB1 and ‘Moonlight’ at TVRF and LB2.

Discussion

The APSIM-potato model used in this study realistically reproduced the observed tuber dry matter yield and nitrogen uptake for the base cultivar ‘Russet Burbank’ as well as for ‘Moonlight’. Additionally, the model captured the growth pattern over the growing period for tuber yield, aboveground biomass, LAI and total plant nitrogen uptake across the on-farm plots and for both cultivars. The low normalized RMSE values obtained are an indication of high precision and reliability of the APSIM-potato model to predict tuber yield. The prediction varied per site with best-fit between the observed and actual data at LB1 for ‘Russet Burbank’ and at TVRF for ‘Moonlight’.

Simulation results for the phenology were reasonable. For both cultivars and across the trial sites, the model realistically predicted the date of emergence (i.e. end of stage code 2), the duration of vegetative stage (SC3) and early tuber (SC4). The model, however overestimated the duration of the later growth stages in particular late tuber (SC5) and in turn, this pushed the start and end of senescence (SC6) and maturity stage (SC7). The model tended to underestimate the rate of senescence of haulms as the crop was harvested when the haulms were completely senesced and the model was still indicating the crop to be at SC5 for 'Russet Burbank' and SC for 'Moonlight' (Fig.3.4).

The overall agreement of aboveground biomass, LAI, leaf, and stem total nitrogen were modest and inferior to that of tuber dry matter yield, and tuber nitrogen uptake. Simulated values for LAI values were close to the observed values for both 'Russet Burbank' and Moonlight during the vegetative and early tuber growth stage (up to 60 DAP for 'Moonlight' and 80 DAP for 'Russet Burbank'). In the later growth stages, simulated LAI were lower for 'Russet Burbank' and higher for 'Moonlight'.

Crop growth models have been shown to vary widely including the ability to simulate different organs of the plant (Asseng et al. 1998; Wolf & Van Oijen 2003). Also, there are differences in precision and ability of crop growth models to simulate different plant organs and no single model is indisputably robust and accurate across cultivars, seasons and environment (Palosuo et al. 2011). When using SUBSTOR-potato model to simulate yield parameters and end of season tuber yield with data from 87 field experiments obtained from 19 countries, Raymundo et al. (2017) reported good agreement between simulated and observed data for tuber yield in majority of the sites. However, simulation results for both LAI and tuber N uptake sometimes differed from the measured values.

In a study by Pembleton et al. (2013), APSIM was shown to have excellent ability to predict forage crop yield and, in most cases, crop development for a range of forage crops but it performed poorly in simulating crop phenology of forage rape and forage sorghum. Nemecek (1996) reported a good agreement for tuber dry matter yield and leaf biomass dry weight but poor fit for stem biomass dry weight with Johnson-potato model. Wolf and Van Oijen (2003) reported a good prediction of tuber dry matter yield using LPOTCO-potato in half of the trial sites and poor prediction in the remaining half of the experimental locations. This seems to have been the case in the present study with good simulation results for tuber yield for both cultivars across the on-farm plots but with variation in leaf and stem state variables and also in phenology, N-uptake per organ and LAI and especially when the model is still new as is the case for APSIM-potato. Similar performances are reported for some of the APSIM plant models. For example, maize grain yield was simulated well in some cropping seasons and poorly in some seasons with APSIM-maize (Shamudzarira & Robertson 2002). Asseng et al. (1998) reported an excellent simulation for wheat grain yield and phenology but poor LAI prediction using APSIM-wheat.

A possible reason for large deviations between simulated and observed leaf and stem biomass in the present study is that the model is programmed to simulate leaf organ without leaf petiole (leaf petiole is simulated in stem organ) while during the field measurement leaf petiole was included in sampling of leaf biomass. Thus N-RMSE and EF for aboveground biomass (leaf and stem combined) is better than for individual leaf and stem (Table 3.5 and 3.6). As shown graphically in Fig.3.5, stem organ is modelled as monotonically non-increasing/decreasing after the peak is achieved (i.e. stem senescence is not modelled).

Given that APSIM-potato is a fairly new model (Brown et al. 2011) compared to other APSIM plant models and that this is the first time it has been tested outside New Zealand, the simulation results are quite encouraging. The simulation results presented here serves as a starting point for other researchers in the field of potato modelling with APSIM-potato and thus further refining is expected as more information is made available.

There is no modelling studies in literature available on the APSIM-potato beside the one describing the model. Brown et al. (2011) reported an excellent best-fit for tuber dry matter yield and nitrogen uptake as well as for leaf and stem biomass and nitrogen uptake. Although such high level of agreement between simulated and observed values was not obtained in the current study for the cultivars and sites investigated, the current modelling exercise have provided new insights on the model performance under Tasmanian potato growing conditions and has increased confidence in the use of model to predict tuber yield and nitrogen content and in other research areas including scenario analysis and climate change impact studies on potato productivity. However, the model is not yet at a stage where it could reliably be used to manage potato production, particularly with respect to N inputs, and the assessment of which SC of the crop should be at in a given period of crop growth. Comprehensive long-term experimental data sets are therefore needed to further improve the model predictive ability of the latter phenological stages and other plant organs across cultivars and environments.

Conclusion

The ability and precision of the APSIM-potato model to simulate tuber dry matter yield and N-uptake was superior compared to simulation of LAI, leaf and stem biomass. The model captured the growth pattern over the growing period for all the crop parameters simulated:

tuber yield, aboveground biomass, LAI and total plant nitrogen uptake per organ for both cultivars and across the on-farm plots. Interestingly, the low ability for the model to reproduce observed values of aboveground and LAI in the locations investigated did not compromise the simulation of the economical yield. However, modification of some key crop specific parameters is needed to improve the predictions of other plant organ growth and development. As part of refining the model, more testing of its performance under is recommended since it was only tested for one cropping season and for only limited management options.

Whilst the data used in the study is limited to one cropping season, our results have provided insights on the model performance under Tasmanian potato growing conditions and has increased confidence in the use of model to predict tuber yield and nitrogen content. Based on its ability to realistically simulate in-season and end-of-season tuber yield, the model could be used to assess impact of climate change on potato productivity under Tasmanian conditions.

Acknowledgements

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Chapter 4 : Parameterization and evaluation of the APSIM-Potato model for tropical low-input farming systems.

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Abstract

Three potato genotypes (‘Unica’, ‘Shangi’ and CIP accession number 300046.22) were grown and soil, climate and potato data for were collected, analysed, and used as inputs for the parameterization and evaluation of the APSIM-potato model. The potato plots were established at the Kabete University Farm in the short rains (SR) of 2013 comparing rain-fed conditions with supplementary irrigation, and in the long rains (LR) of 2014 with supplementary irrigation and comparing three nitrogen fertiliser levels (N23, N63 and N104). For all the genotypes, and across all treatments, the model realistically captured the growth pattern and partitioning of assimilates to the tuber state variable over time with fair to good index of agreement both in the SR2013 experiment (N-RMSE = 19.5%, EF = 0.94 for rain-fed; N-RMSE = 17.9%, EF = 0.95 for supplementary irrigation treatment) and in the LR2014 experiment (N-RMSE = 22.8%, 31.4%, 31.4% and EF = 0.93, 0.88

and 0.89 for the N23, N63 and N104 nitrogen levels respectively). Overall, the model realistically reproduced tuber dry matter yield in the SR2013 experiment with mean yield under rain-fed conditions of 3.8 ±0.13 t ha^{-1} compared to simulated values of 4.4 t ha^{-1} and with supplementary irrigation 6.2 ±0.23 t ha^{-1} compared to simulated tuber yield of 6.2 t ha^{-1}. In the LR2014 experiment, the model underestimated tuber yields with the mean simulated value across the nitrogen levels of 6.5 t ha^{-1} compared to the measured value of 7.7 ±0.41 t ha^{-1}. This was the first time the model was tested under Kenyan conditions. Based on the model's ability to simulate tuber yield, the results have increased confidence in the use of APSIM-potato for modelling studies. Strategies to refine APSIM-potato for application to Kenyan cultivars is discussed.

Keywords: APSIM-potato, parameterization, evaluation, simulation, phenology, tuber dry matter yield

Introduction

Many households in Kenya, and other developing countries, depend on the potato (*Solanum tuberosum* L) as a source of food and nutrition (Lutaladio et al. 2009; Lizana et al. 2017). The potato has been an important food crop in Kenya since its introduction in the late 19th century. Despite its role as one of Kenya's strategic food commodities in food security, growth in the industry is constrained by many factors but the most important are; shortage of quality seed tubers, limited choice of adaptable high yielding cultivars, high pest and disease incidence, suboptimal production practices, unreliable rainfall patterns, poor postharvest practices, poor infrastructure, and low value addition (Kaguongo et al. 2013). Climate change, climate variability, and an over reliance on rain-fed growing conditions are emerging threats to the potato industry.

Modelling is a fast and inexpensive way to enhance research and the simulation results can be used to inform farmers, agronomist and policy makers or to adopt new farm practices (Carberry et al. 2002; Oteng-Darko et al. 2013; Angulo et al. 2013.). The use of crop simulation models to quantify yield gaps or to assess potential benefits of various management options or to conduct vulnerability, impacts and adaptations (VIA) to climate change for the potato has lagged behind other majors crops such as wheat, rice, and maize (White et al. 2011) yet potato is the third most important food crop globally (Bradshaw & Bonierbale 2010; Birch et al. 2012). A few potato modelling studies have been conducted at a global (Hijmans 2003; Luck et al. 2011; Kroschel et al. 2013), regional (Tubiello et al. 2002; Holden & Brereton 2006) or country scale (Harahagazwe et al. 2012; Saue & Kadaja 2014; Svubure et al. 2015; Resop et al. 2016).

In recent years, a number of initiatives aimed at improving the potato industry were implemented including introduction of rapid seed multiplication technologies in particular aeroponics, training of growers in alternative seed production methods such as positive selection, and good cultural practices, fast-tracking registration of improved varieties, and encouraging private sector involvement. While these initiatives improved productivity, yield gaps still exist, partly due to low adoption rates among farmers (Kaguongo et al. 2013). Crop simulation modelling can be used to explore these constraints and evaluate opportunities (Oteng-Darko et al. 2013; Van Wart et al. 2013; Grassini et al. 2015). Crop growth models can also be used to assess the potential impacts of climate change on future potato productivity. For this to be done, a robust and reliable crop growth model is needed.

The first potato model was developed about five decades ago (Sands et al. 1979). Since then, over 30 potato crop growth models have been developed (Raymundo et al. 2014). The most significant ones include SUBSTOR-Potato, LINTUL-Potato, SOLANUM, APSIM-Potato, SPUDSIM, POMOD, SIMPOTATO and Potato Calculator (Raymundo et al. 2014; Saue & Kadaja 2014; Resop et al. 2016; Fleisher et al. 2017). There are few modelling studies but a high number of potato models. Reasons for this might include the difficulty in modelling potato plants due to large variation in the ploidy, its indeterminate growth pattern and lack of discrete developmental stages as compared to other crops (Fleisher et al. 2017). Difficulties in quantifying the physiology of potato and in observing growth and development of below ground economical yield component has also contributed to few potato modelling studies (Brown et al. 2011). According to Raymundo et al. (2014) and Fleisher et al. (2017) most potato crop models have not been comprehensively tested with actual field data and thus are not capable of simulating new conditions, such as the effect of climate change.

This study uses the APSIM-potato (Brown et al. 2011), a new plant models built within the APSIM modelling framework (Brown et al. 2011). The decision to use the model was based on the extensive application, acceptability, and accessibility of the APSIM modelling framework within the developing world. Moreover, there is a growing interest in the APSIM modelling framework in African countries including Kenya, South Africa, Zimbabwe, and Ethiopia, where significant APSIM downloads were recorded in 2013/14 (Holzworth et al. 2014).

Before crop growth models can be applied in new areas or with new cultivars, accurate parameterization with data from field grown crops is required (Boote et al. 2010; Palosuo et al. 2011; Raymundo et al. 2014). This study was the first time that APSIM-potato was tested under Kenyan conditions. Previously, APSIM-potato had only been tested and calibrated with a number of data sets from a long-term experiment conducted in Lincoln, New Zealand where it accurately reproduced with the cultivar 'Russet Burbank' the effects of different rates of N-fertilizer, sowing dates, plant density, and irrigation treatments (Brown et al. 2011). However it was recognized that further parameterization and evaluation was required using field data from different locations and cultivars.

Compared to high input system in New Zealand where the model was calibrated, Kenya like many other countries in Sub-Saharan Africa (SSA) is a low input system in relation to water and fertiliser usage (Fox et al. 2005). SSA has the lowest fertilizer application rates globally with only 8 kg/(ha year), against a world average of 93 kg/(ha year) and 200 kg/(ha year) in East Asia (Marenya & Barrett 2009). Limited access to credit, lack of information on appropriate fertilizer use and inefficient infrastructural and institutional systems that limit availability of fertilizer contribute to low application rates in Kenya (Duflo et al. 2007). Additionally, crop production in Kenya, including potato production, is predominantly grown under rain-fed conditions (Kaguongo et al. 2013).

If confidence in APSIM-potato's ability to realistically simulate potato systems could be established then the use of the model to simulate tuber yield and resource use could assist decision-making around smallholder potato production in Kenya. Thus, the objectives of this study was to; (i) parameterize the APSIM-potato model and, (ii) evaluate the model's performance in simulating in-season and end-of-season biomass, and tuber yield of different potato cultivars under Kenyan conditions. This study also addressed the need to test APSIM-model performance under suboptimal heat and water stress conditions.

Materials and Methods

Site description

Field experiments were conducted at The University of Nairobi, Kabete Farm, (1.25S, 36.73E, 1840 AMSL) during the 'short rains' (SR2013) and 'long rains' (LR2014). The farm is located approximately 15 km North-West of Nairobi in the Central region of Kenya. The rainfall pattern in Central Kenya is bimodal with LR during the MAM (March-April-May) months and SR occurring in OND (October-November-December) months. The soils in the region are predominantly Nitosols (Nyandat 1977).

The SR2013 experiment was planted on November 4, 2013 and the LR2014 experiment was planted on April 3, 2014. At planting, approximately 100 g of soil samples, down to a 0.6 m depth, were collected in duplicates from each block using hand soil augurs. Samples were analysed using the standard set of increments: 0-0.15, 0.15-0.3, 0.3-0.6 m (Table 4.1). One set of soil samples were used for determining initial gravimetric soil water content (θg) by oven drying the samples at 105 °C to a constant weight for at least 48 hours (Cresswell and Harmilton 2002). Soil chemical analysis was done using the second set of soil samples (Table 4.1) using the analytical techniques described in Hinga et al. (1980) and Landon (1991).

At the SR2013 experiment site, pH was within the optimum range and slightly lower at the LR2014 site (Table 4.1). Potato is well suited to acidic soil with an optimum pH range of 5.8 to 6.8 (Lutaladio et al. 2009). In both sites, soil K was considered to be sufficient but P and N was considered to be insufficient thus N and P fertilizers were applied at planting. Since most field crops prefer soils with very low EC levels (<0.15 ds m^{-1}) to low (0.15 to 0.45 ds m^{-1}) (Rayment & Lyons 2011), values of EC in both sites was considered to be favourable for potato growth.

Table 4.1 Initial soil water content (VWC) and soil chemical properties at the SR2013 and LR2014 experiment sites**.**

Season	**Depth**	**VWC**	**EC**	**pH-H_2O**	**P**	**K**	**NO3-N**	**NH4+**	**OC**
	(cm)	(mm/mm)	(dS/m)	(1:5)	Mg/kg		Kg N/ha		(%)
SR2013	00-15	0.2	0.2	6.4	13.7	526	6.6	9.4	2.9
	15-30	0.3	0.1	5.8	13.3	585	5.7	6.8	2.5
	30-60	0.3	0.2	6.5	16.6	585	1.2	6.6	2.4
LR2014	00-15	0.3	0.2	4.9	9.6	507	7.6	13.6	2.9
	15-30	0.3	0.1	5.1	9.2	468	5.9	13.1	2.9
	30-60	0.3	0.2	5.3	7.5	468	4.5	9.6	2.8

P: Colwell Phosphorus, K: Colwell Potassium, NO3-N: Nitrate nitrogen, NH4+: Ammonium nitrogen, EC: Electrical conductivity, OC: Organic Carbon, VWC: Volumetric soil water content.

Experimental design, genotypes and cultural practices

The design for the SR2013 experiment was a split-plot with two water levels (supplementary irrigation and rain-fed) as the main plot factor and three genotypes as the sub-plot factor, with four replications (blocks). A randomized complete block design (RCDB), was used in the LR2014 experiment, with three nitrogen levels (i.e 23, 63 and 104 kg N ha^{-1}, hereafter referred to as N23, N63 and N104 treatment levels) and four replicates. The N23 and N63 treatment levels mimicked the amounts of nitrogen applied by different categories of farmers and N104 represented the Ministry of Agriculture recommended rate for potato production. Most farmers use suboptimal amounts, usually about a quarter (represented by N23) or half (represented by N63) of the recommended amounts.

The genotypes used both in the SR2013 and LR2014 included two advanced clones from the International Potato Center (CIP): CIP accession number 392797.22 (hereafter referred to as cultivar Unica, the commercial name of the clone in Peru where it was first registered), and CIP accession number 300046.22 (hereafter referred to as CIP 300046.22). Both 'Unica' and CIP 300046.22 belong to the Lowland Tropics Virus Resistance (LTVR) population. The LTVR programme aims to develop cultivars with tolerance to heat under both arid and humid conditions by promoting early tuberization under short days, and mid-maturity under long days (Gastelo et al., 2014). To complement heat tolerance, emphasis is on resistance to viruses, particularly PVY and PVX and increased levels of quantitative resistance to PLRV.

The third genotype used in the study is 'Shangi', a farmer-selected cultivar. Adopted by farmers in Kenya between 2009 and 2010, 'Shangi' was officially registered in March 2015. By the time of official registration, it was the most preferred cultivar by farmers, traders and consumers alike. Size 1.0 grade (average 60 g) of sprouted whole tubers were used for both seasons, except for 'Unica' where size 2 minitubers (average 20 g) were used in the SR2013 experiment, as field tubers were not available. Both 'Unica' and CIP 300046.22 had performed well in previous performance experiments in Kenya in terms of tuber yield and disease resistance. In the preliminary experiment conducted during the

LR2013 (MAM), (data not shown) 'Unica' produce the highest yield of 25.8 t ha^{-1} fresh weight (Fw) and 'Shangi' produce tuber yield of 10.4 t Fw ha^{-1}.

Tubers were manually planted 0.1 m deep with a row spacing of 0.75 m and intra-row spacing of 0.3 m (4.4 tubers m^{-2}). Two outer rows were established as border rows. Each sub-plot (SR2013) and plots (LR2014) measured 16.2 m^2 with 72 plants in six rows of 12 plants. Although the tubers were planted at about 0.1 m deep, the ridges were raised to about 0.2 m before tuber initiation growth stage. In the SR2013 experiment, diammonium phosphate fertiliser (18-46-0) was applied at planting at a rate of 500 kg ha^{-1}, the recommended fertilizer application for potato production in Kenya. In the LR2014 experiment the same fertilizer (18-46-0) at a rate of 125 kg ha^{-1} and triple superphosphate (0-46-0) at 375 kg ha^{-1} were applied at planting. This amount translates to 23 kg N and 90 kg P ha^{-1} (i.e. N23 treatment plots). Additional nitrogen was applied as calcium ammonium nitrate (CAN, N27 with traces of calcium and magnesium) to N63 treatments plots at a rate of 20.3 kg N ha^{-1} (i.e. 63 kg N ha^{-1}) and in N104 treatments plots at a rate of 40.5 kg N ha^{-1} (i.e. 104 kg N ha^{-1}) two weeks after emergence and the same amounts were applied at the start of flowering (10% flowering). No additional nitrogen was applied in the N23 treatment plots.

For the crop that received supplementary irrigation in the SR2013 experiment and the whole field for the LR2014 experiment, the plan was to maintain adequate soil moisture through irrigation. However, this was not possible due to frequent breakdown of irrigation facilities. Consequently, only a total of 92 mm (4 irrigation events) of water was applied during the SR2013 and 78.6 mm (3 irrigation events) during the LR2014 growing season.

The irrigation was applied at 40, 53, 71, and 86 days after planting (DAP) in the SR2013 and at 26, 46, and 53 DAP in the LR2014 experiment. Fields were sprayed every fortnight with fungicides to control late blight (*Phytophthora infestans*). In the SR2013 experiment, the crops were also sprayed with pesticides to control virus causing aphids and potato tuber moth (PTM) (*Phthorimaea operculella*), as presence of aphids and PTM were noticed towards the end of the season. Harvesting was done manually when the haulms were completely senesced, although dehaulming was necessary for the 'Unica' and CIP 300046.22 due to a wet end of the season during the SR2013 experiment that lead to regrowth. Because of its short growth cycle, dehaulming was not necessary for 'Shangi' since it had fully senesced by the time it rained again towards the end of February 2014.

Weather data

Daily weather data used in the study to run the simulations were obtained from Kenya Meteorological Department (KMD) for Kabete Station located within the Kabete Farm and close to the sites where the experiments were conducted. Since solar radiation data were not recorded at the Kabete station, solar radiation data for Dagoretti Corner Meteorological Station (1.37S, 36.73E) which is located approximately 5 km from Kabete Farm were obtained. Missing and outlying weather data were substituted with data from the NASA database, (http://power.larc.nasa.gov).

Daily maximum temperature (Tmax), minimum temperature (Tmin), solar radiation, and monthly rainfall during both SR2013 and LR2014 cropping seasons are presented in Fig.4.1. The difference in daily mean temperature between the two seasons was minimal but solar radiation and total in-crop rainfall was much higher in the SR2013 cropping season (Table 4.2). With a temperature of 2 °C, (Tbase for potato) accumulated growing day degrees (°Cd) from planting to final harvesting of the last genotype to be harvested was 2089 °Cd for SR2013 and 1998 °Cd for LR2014. Total in-crop rainfall received was 377 mm for SR2013 and 266 mm for LR2014. Although more rainfall was received during the SR2013, (Fig.4.1), the distribution was uneven with substantial amount received after tuber bulking. Tuber initiation and tuber bulking are the most sensitive growth stages to water stress (MacKerron & Jefferies 1988; Haverkort 1990; Yuan et al. 2003).

Table 4.2 Weather data (temperature, solar radiation and rainfall) and accumulated growing day (GDD) from planting to harvesting during the SR2013 and LR2014 cropping season.

Data	**Units**	**SR2013**	**LR2014**
Max. radiation	MJ^2/day	30.6	30.4
Min.radiation	MJ2/day	10.4	4.3
Avg. Tmax	˚C	24.2	23.3
Avg. Tmin	˚C	14.1	13.7
Mean Temp	˚C	19.1	18.5
Total in-crop rainfall	mm	377	266
Accumulated GDD (°Cd) at final harvest	˚Cd	2089	1998

Measurements of field data

Crop measurements

Sampling of the potato plants started from December 13, 2013 (29 DAP) for the SR2013 experiment and from May 1, 2014 (28 DAP) for the LR2014 experiment, and continued on weekly basis throughout the growing season. Crop emergence was measured by counting the number of emerged plants in each plot and was assumed to have taken place when 50% of the plants had emerged from the soil surface. For each sequential harvesting, 4 plants per plot were harvested. Growth and development parameters including the height of the main stem (MS), number of MS, number of tubers per plant, and the number of leaves appearing on each MS for every sampled plant were recorded immediately after each sequential harvesting before the plants were separated into leaves (L, the whole compound leaf including petioles), stems (S) which included below and aboveground stems) and tubers (T). Roots and stolons were discarded because they are not economically important, difficult to measure, and are a minor component of biomass.

Fresh weights of the 4 harvested plants separated into the three plant organs (L, S and T) were recorded. The dry weight of each organ was determined by oven drying the sub-samples at 90 °C for 48 hours or until a stable mass is reached. Where samples were too bulky, a sub-sample of about 300 g per organ was taken for drying. Sampling of leaf and stem organs was stopped following senescence (>50%) of the haulms.

Bulk density and soil hydraulic properties

After harvesting, freshly-excavated soil pits were used to describe and characterise the soils at each experimental site. Depending on the soil horizons, samples were collected at 0.2 to 0.3 m intervals from the soil surface to a depth of 1.4 m. Soil cores were collected using rings with a height of 57 mm and 40 mm internal diameter for the SR2013 experiment and rings with a height of 50 mm and an internal diameter of 50 mm for the LR2014. In each site and for each soil layer, five soil cores were collected. The rings were hammered vertically into the steps made on the wall of the soil pit at each layer and the cores were carefully trimmed both at the top and bottom end.

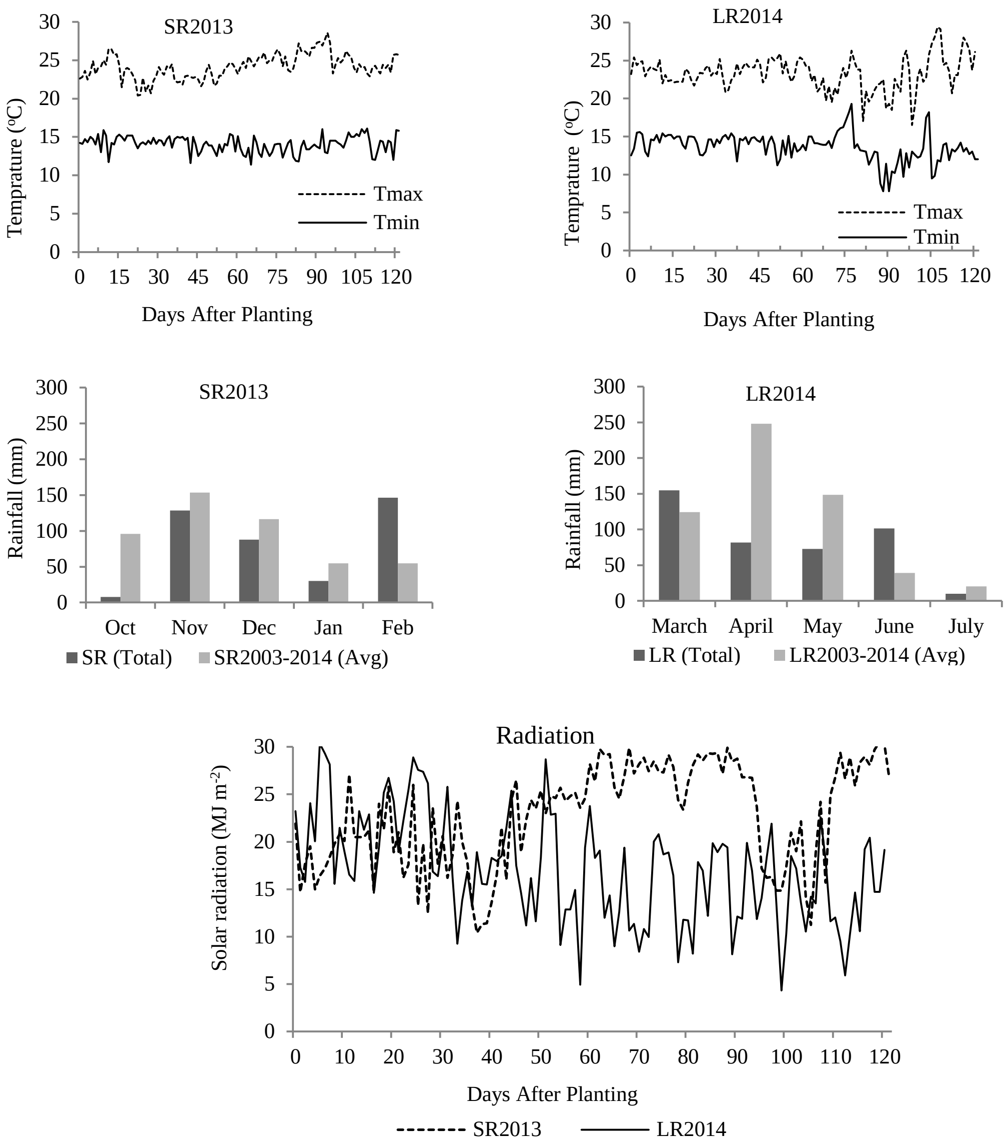

Figure 4.1 Daily maximum (Tmax) and minimum (Tmin) temperature, average monthly total rainfall and daily solar radiation during the SR2013 and LR2014 cropping seasons and for the period 2003-2014, Kabete farm

During the collection of soil cores care was taken to ensure soil disturbance was minimal. Two sets (2 replication) of soil cores were used for determination of bulk density (BD) and soil texture, and three sets (3 replications) were used for determination of soil water properties: plant available water content at saturation (SAT), drained upper limit (DUL) and crop lower limit (LL15) using the soil physical analytical methods described in

(Landon 1991) at the Soil Laboratory, Kabete Campus (Table 4.3). Air-dry values were estimated using LL15 values. Soil cores used for determination of BD were oven dried at 105 °C to a constant weight for at least 48 hours. BD expressed in g cm^{-3} is the ratio of dry soil mass to the total volume of dry soils (Cresswell & Harmilton 2002). According to (Landon 1991), root penetration is hindered by bulk densities above 1.75 for sands or 1.63 g cm^{-3} for silts and clay and hence the values at both sites (Table 4.3) were considered not cause any hindrance to potato root development.

Standard commercial pressure plate extractor (1600,5 Bar Ceramic Plate Extractor) was used to determine SAT, DUL and LL15 equilibrated at specified matric potential: 0 kPa for SAT, -10 kPa for DUL and -1500 kPa for LL15. One plate containing samples for one replicate was placed in the pressure chamber at a time and each plate was pressurized until the soil cores have attained equilibrium, on average for 5 to 7 days. Once equilibrium was reached, soil cores were removed from the ceramic plate and weighed and then returned to the ceramic plate for the next matric potential as the most negative matric potential was the last to be determined. Once the last samples attained equilibrium with the last matric potentials, the soil cores were oven dried at 105 °C to a constant weight for at least 48 hours. Volumetric water content at a given matric potential was calculated (Table 4.3).

In APSIM, potential crop water uptake is simulated via relationships with root exploration factor (XL) and potential water extraction coefficient (KL), which depends on soil and crop factors (Keating et al. 2003). Based on the soil properties (Table 4.3), potato XF was set at a value of 1 for all the soil layers down to a maximum depth of 0.9 m based on the assumption that the rooting capability between soil layers was not restricted. KL values were adjusted based on the fact that approximately 85% of potato roots are concentrated in the upper 0.3 m soil layer (Vos & Groenwold 1986; Opena & Porter 1999), although roots can be found down to 1m depending on the cultivar and soil type. Thus for the upper soil layers (0 to 0.3 m) with high root length densities a KL value of 0.1 was used. Since root length densities are low at soil depth below 0.3 m, KL value was therefore reduced to 0.03 for depths ranging between 0.3 and 0.65 m and to 0.01 m for depths between 0.65 and 0.95 m.

Table 4.3 Soil bulk density, plant available water content at saturation (SAT), drained upper limit (DUL) and crop lower limit (LL15) and air dry of the soil samples taken to a depth of 1.2 m at the SR2013 and LR2014 experiment site as input parameter data to run the simulations.

Depth	**BD**	**Air dry**	**LL15**	**DUL**	**SAT**
(cm)	(g cm^{-3})		(mm mm^{-1})		
SR2013					
0-21	1.01	0.2	0.22	0.29	0.46
21-40	1.14	0.26	0.26	0.33	0.47
40-65	1.12	0.26	0.26	0.34	0.49
65-105	1.16	0.27	0.27	0.34	0.47
105-140	0.10	0.23	0.23	0.34	0.48
LR2014					
0-21	0.94	0.20	0.24	0.31	0.64
21-40	1.01	0.24	0.24	0.34	0.61
40-65	1.04	0.26	0.26	0.35	0.59
65-105	1.05	0.27	0.27	0.33	0.53
105-140	1.13	0.28	0.28	0.34	0.53

Model parameterization and evaluation

The Model

This study used APSIM-potato (version 7.5), a new plant model built in the Plant Modelling Framework (Brown et al. 2014) and described in detail by (Brown et al. 2011). In brief, APSIM-potato is a comprehensive daily time-step, deterministic crop model that integrates with the APSIM soil, SOILN, management, and user interface components to provide robust and user friendly simulations.

The model predicts biomass, tuber yield, N-uptake, water use efficiency of the potato plant, soil water variables and other plant parameters on a daily basis in response to inputs of daily weather data, soil characteristics, crop parameters and management events. It uses a constant RUE (Radiation Use Efficiency) value of 1.2 g dry matter/MJ of intercepted radiation. The water stress factor (f_w) is optimum at 1.0 when the crops are supplied with adequate water and will decline to zero when the soil moisture is nearing the crop lower limit (LL15) (Lobell et al. 2015). At daily average temperatures of 2 °C (Tbase), the temperature stress factor (ft) values rises from zero to a maximum value of 1.0 at daily mean temperatures of between 12 and 24 °C. Above 24 °C, the ft values declines to zero at 34 °C.

Using inputs of tuber planting density and the number of main stems per tuber, the model calculates the population density of primary stem units which are in turn used to predict the rate of appearance, expansion, size and duration of individual leaves on the primary stems and the occurrence of branching. APSIM-potato partitions dry matter assimilates into four state variables: leaf, stem, root and tuber.

Model parameterization

The experiments described above were simulated using APSIM-potato with the measured weather, soil and crop data, and management events. Daily weather data (global incoming solar radiation, rainfall, maximum and minimum temperatures) used in the simulations are presented in Fig.4.1. Soil chemical properties: initial organic carbon content (OC), Nitrate nitrogen (NO_3-N), Ammonium nitrogen (NH_{4+}), pH-H_2O, electrical conductivity (EC) and initial volumetric soil water content (Table 4.1); soil hydraulic properties; SAT, DUL, CLL; air dry and bulk density data (Table 4.3) were used as input data to initialise the simulations. Crop data and management events are summarized in Table 4.4. Though the actual sowing depth was 0.1 m, the depth used to run APSIM for 'Unica' and CIP 300046.22 was changed to 0.15 m in order to get the observed sprout emergence date as close as possible to the simulated date.

Crop growth models require parameterization of the default crop parameters before the models can be applied to new cultivars (Palosuo et al. 2011). In each of the APSIM crop models, there are two major parts; the crop-specific constants and cultivar-specific parameters (Keating et al. 2003). The cultivar-specific parameters can be overridden where a cultivar is distinctly different from the model base cultivar (which is 'Russet Burbank' in the case of APSIM-potato). Measured data for the three genotypes were grouped into data that were used to set up the model (number of main stem plant^{-1}, number of leaves MS^{-1}) and the data used to evaluate the model (aboveground biomass, tuber yield, N-uptake, LAI).

‘Russet Burbank’, a worldwide commercial processing cultivar is adapted to long day conditions, whereas the genotypes used in Kenya are adapted to short day conditions. Photoperiod and temperature are key climatic factors that influence tuber production (Kooman et al. 1996), affecting biomass assimilation, organ partitioning, specific leaf area, canopy structure, and tuber size distribution and number. ‘Russet Burbank’ is of the *tuberosum* subspecies and is a late maturing cultivar in which tuber initiation and canopy development takes place over a relatively longer period (Beattie 2010). The three genotypes used in the study belong to the *andigenum* subspecies characterised by a relatively shorter growth cycle with intermediate bulking initiation and fast-bulking rates (Condori et al. 2010).

Table 4.4 Crop and management events at the SR2013 and LR2014 experimental sites that used as input parameter data to run the simulations**.**

Season	**SR2013**			**LR2014**		
Events	‘Shangi’	‘Unica’	CIP 300046.22	‘Shangi’	‘Unica’	CIP 300046.22
Planting date	4 Nov. 2013	4 Nov. 2013	4 Nov. 2013	3 April 2014	3 April 2014	3 April 2014
Emergence date	24 Nov. 2013	29 Nov. 2013	28 Nov. 2013	21 April 2014	27 April 2014	26 April 2014
Sowing depth (mm)	100	150	150	100	150	150
Row spacing (mm)	750	750	750	750	750	750
Inter row spacing (mm)	300	300	300	300	300	300
Plant density (plants m^{-2})	4.4	4.4	4.4	4.4	4.4	4.4
No.of MS/plant	2.7	1.4	1.5	2.40	1.4	1.6
Stem density (stems m^{-2})	12.3	6	6.8	10.8	6.3	7.2
N-application (Kg N/ha)	90	90	90	23,63,104	23,63,104	23,63,104
Irrigation water applied (mm)	92	92	92	78.6	78.6	78.6
Harvesting date	24/2/2014	24/2/2014, 5/3/ 2014	24/2/2014, 5/3/ 2014	25/7/2014	1/8/2014	1/8/2014
Duration of growing season (days)	112	112,121	112,121	113	120	120

MS: main stem. [1]In the SR2013 experiment, the rain-fed crop was harvested earlier than supplementary irrigated treatment.

Out of the three genotypes used in the experiments, ‘Shangi’ is an early maturating (90 days) cultivar with an earlier tuber initiation period and a faster bulking rate compared to ‘Unica’ and CIP 300046.22, both of which are medium maturing (90-120 days) genotypes. The three genotypes also vary in terms of plant height, leaf area and potential tuber yields. For example, in both seasons, ‘Unica’ and CIP 300046.22 had the maximum leaf area between 80 and 90 days after planting (DAP) compared to ‘Shangi’ which had the maximum leaf area between 50 and 65 DAP. Based on these differences and similarities, we parameterised the model by adjusting some of the cultivar-specific parameters for each genotype. The changes were guided by field observations of the phenology, leaf duration and final number of leaves on the main stem relative to the default parameters in the model. We adjusted six cultivar-specific parameters: (i) Main stem final node number, (ii) Phenology vegetative target, (iii) Stem branching rate, (iv) Leaf maximum area, (v) Leaf lag duration, and (vi) Tuber dry matter demand function. The other cultivar-specific parameters were assumed the same to the values of the base cultivar, ‘Russet Burbank’ and were left unchanged. All the crop-specific constants were left unchanged.

Model evaluation

The parameterized APSIM-potato was used to run the simulations and the performance of the model was assessed by comparing simulated crop data with the measured crop data. Measured biomass (leaf and stem combined) and tuber dry matter yield were compared with the simulated data. All the comparison was done on a dry weight basis.

Model evaluation statistics

Statistical analysis of the data was carried out using SAS (SAS® 9.3 Software, 2011). The model reliability in replicating biomass, and tuber yield was evaluated using normalized Root mean squared error (RMSE expressed as %), an error index statistics that gives a measure of the relative difference of simulated verses observed data (Soler et al. 2007), and modelling efficiency (EF), a dimensionless statistic that gives an assessment of model performance (Moriasi et al. 2007). RMSE (Eq.1) (Soler et al. 2007) was normalised by the mean of observed values. The agreement between the simulated and the observed data is considered excellent if the normalised RMSE (N-RMSE) value is less than 10%, a value of 10 to 20% is considered good, a value of 20 to 30% is viewed as fair while the agreement is considered poor if the N-RMSE value is greater than 30% (Soler et al. 2007). An EF (Eq.2) (Krause et al. 2005) value of 1.0 is considered excellent, values ranging from 0.0 to >1.0 are considered acceptable and the level of performance is considered poor if the values are less or equal to 0.0 (Loague & Green 1991; Moriasi et al. 2007). RMSE and EF are often used in model performance evaluation including in previous potato modelling studies (Tubiello et al. 2002; Condori et al. 2010; Carli et al. 2014).

$$N-RMSE = \sqrt{\frac{\sum_{i=1}^{n}(S_i-O_i)^2}{n}}\ x\,\frac{100}{M} \quad (1)$$

$$EF = 1 - \frac{\sum_{i=1}^{n}(O_i-S_i)^2}{\sum_{i=1}^{n}(O_i-\bar{O})^2} \quad (2)$$

Where n is the number of observations, S_i refers to the simulated values, O_i refers to the observed values of potato crop data e.g. biomass dry weight or tuber dry matter yield and M (Eq. 1) and $\bar{O}$ (Eq. 2) refers to the mean of the observed values.

Results

Effect of supplementary irrigation and nitrogen on biomass and tuber yield

Effect of irrigation

In the SR2013 experiment, supplementary irrigation had a significant effect on the end-of-season tuber yield and marketable yield expressed as percentage of total fresh tuber yield (Table 4.5). When averaged across cultivars, supplementary irrigation increased fresh weight (FW) yield by 13 t $FWha^{-1}$ from 19 to 32 t $FWha^{-1}$. The effect on total and marketable tuber yield was mainly because of improved tuber expansion as indicated by a higher proportion of larger tubers. Smaller tubers (<40 mm, 20.6% and 11.3% of the total tuber yield in the rain-fed and suppl. irrigation respectively) considered unmarketable in the study showed a decline while large tubers (>80 mm, 6.3% and 21.7% of the total tuber yield in the rain-fed and suppl. irrigation respectively) increased in the supplementary irrigation plots compared to rain-fed plots. The effect of supplementary irrigation was due to prolonged leaf duration with rain-fed crop senescing earlier and faster than the crop which received supplementary irrigation. Final harvesting was carried out the haulms were completely senesced; at 113 DAP in the rain-fed plots and 121 DAP in the supplementary irrigation plots.

The LR2014 cropping season was generally drier with less rainfall than the long-term average (Fig.4.1). The dry period during June-July resulted in accelerated senescence which was more pronounced in the 'Unica' and CIP 300046.22 and less in 'Shangi' which has a faster growth rate and is seen to have "escape" the dry period.

Table 4.5 Effect of supplementary irrigation on final fresh tuber yield (t $FWha^{-1}$) and marketable tuber yield of the three potato genotypes planted during the SR2013 cropping season. Values are mean ±SE (n = 4).

	End-of season total fresh tuber yield t FW/ha			**Marketable fresh tuber yield (%)**		
Genotype	Rain-fed	Suppl. Irrigation	Mean	Rain-fed	Suppl. Irrigation	Mean
‘Shangi’	19.2 ± 0.91	30.7 ±1.36	25.0	72.7	84.2	78.4a
‘Unica’	19.8 ± 0.92	33.2 ±1.54	26.5	82.0	85.5	83.8b
CIP 300046.22	18.1 ± 0.82	32.1 ±1.14	25.1	73.4	81.7	77.5a
Mean	*19.0a*	*32.0b*	*25.0*	*76.0a*	*83.8b*	*79.9*
Water level		P = 0.0001			P = 0.0011	
Genotype		P = 0.4713			P = 0.0328	
W * G interactions		P = 0.6400			P = 0.2323	

DAP: Days after planting, FW: Fresh weight, P: Probability level of statistical significant, W* G: water and genotype. Values on the same column and row with no common letter are significantly different (P < 0.05) according to LSD test.

Effect of Nitrogen

In the LR2014, experiment, nitrogen levels had significant effect on total tuber yield and marketable yield expressed as percentage of total fresh tuber yield (Table 4.6). When averaged across nitrogen levels, ‘Unica’ gave a greater tuber yield (41.2 t $FWha^{-1}$) than ‘Shangi’ (33.5 t $FWha^{-1}$) or CIP 300046.22 (33.6 t $FWha^{-1}$). Across genotypes, the tuber yield at N104 treatment was greater than yield for N23 by 7.1 t $FWha^{-1}$. The effect of nitrogen was due to prolonged leaf duration. For example at the time of harvesting, there were differences in the stage of senescence as N23 senesced a few days earlier than N63 and N104. Final harvesting was done when the haulms were completely senesced (i.e. 113 DAP for ‘Shangi’ and 120 DAP for ‘Unica’ and CIP 300046.22).

Table 4.6 Effect of nitrogen level on final fresh tuber yield and marketable tuber yield (%) of the three genotypes planted during the LR2014 cropping season. Values are mean ±SE (n = 4).

Genotypes	**Tuber Yield**	**t FW/ha**			**Marketable fresh tuber yield (%)**			
	N23	N63	N104	Mean	N23	N63	N104	Mean
'Shangi'	30.1 ± 1.60	34.5 ± 1.60	36 ± 1.89	33.5b	88.6	90.7	92.9	90.8
'Unica'	34.4 ± 1.20	43.6 ± 3.08	45.4 ± 1.75	41.2a	90.8	94.9	95.7	93.8
CIP 300046.22	30.9 ± 1.82	34.5 ± 2.10	35.3 ± 1.17	33.6b	91.7	88.2	93.4	91.1
Mean	31.8b	37.5a	38.9a		90.4a	91.3ab	94b	
Genotype		P = 0.0001				P = 0.0655		
Nitrogen		P = 0.0001				P = 0.0316		
N * G interactions		P = 0.3858				P = 0.2531		

DAP: Days after planting, FW: Fresh weight, P: Probability level of statistical significant, N* G: Nitrogen and genotype. N23: 23 kg N ha^{-1}, N63: 63 kg N ha^{-1}, N104: 104 kg N ha^{-1}. Values on the same column and row with no common letter are significantly different (P < 0.05) according to LSD test.

Model evaluation

Number of leaves per main stem (MS)

Generally, simulated rate of leaf appearance was the same or faster than the observed rate except for 'Shangi' during the LR2014 (Fig.4.2). The index of agreement was good across seasons and cultivars with N-RMSE values of 23.1% for the SR2013 and 11.6% for the LR2014. However, modelling efficiency (EF) was poor across seasons and cultivars (average -1.29 in SR2013 and -0.20 in LR 2014), (Fig.4.2).

Aboveground biomass

Simulation results for biomass (dry weight of leaf and stem combined) showed a large variation between the observed and simulated values (Fig.4.3). Compared to tuber yield, simulation results for biomass were poor. In the SR2013 experiment, simulated values across the genotypes were similar to the observed values during the vegetative and early tuber growth stages (up to ~ 45 DAP) but much lower during the following growth stages (Fig.4.3). In contrast, simulated values for the LR2014 experiment were slightly lower or equal to the observed values during the first half of the growth stages (up to ~ 60 DAP) for ‘Shangi’ and ‘Unica’ but higher than the observed values in the latter growth stages in particular for ‘Shangi’. For CIP 300046.22, simulated values were lower than the observed values throughout the growing period. In APSIM-potato, stem organ is modelled as monotonically non-increasing/decreasing after the peak is achieved (i.e. stem senescence is not modelled) and hence the simulated values are not decreasing as is happening with observed data (Fig.4.3).

In both seasons, the index of agreement (Fig.4.3) between simulated and observed biomass value was generally low with an average N-RMSE value of 35.2% across the nitrogen levels and genotypes in the LR2014 experiment. The N-RMSE averaged 47.6% across water levels and genotypes in the SR2013 experiment. In both seasons, the model performance was poor with EF values ranging from -0.8 to 0.9 (averaged 0.1 in LR 2014) while in the SR2013 cropping season, EF values ranged from -0.6 to 0.5 (averaged 0.1), (Fig.4.3).

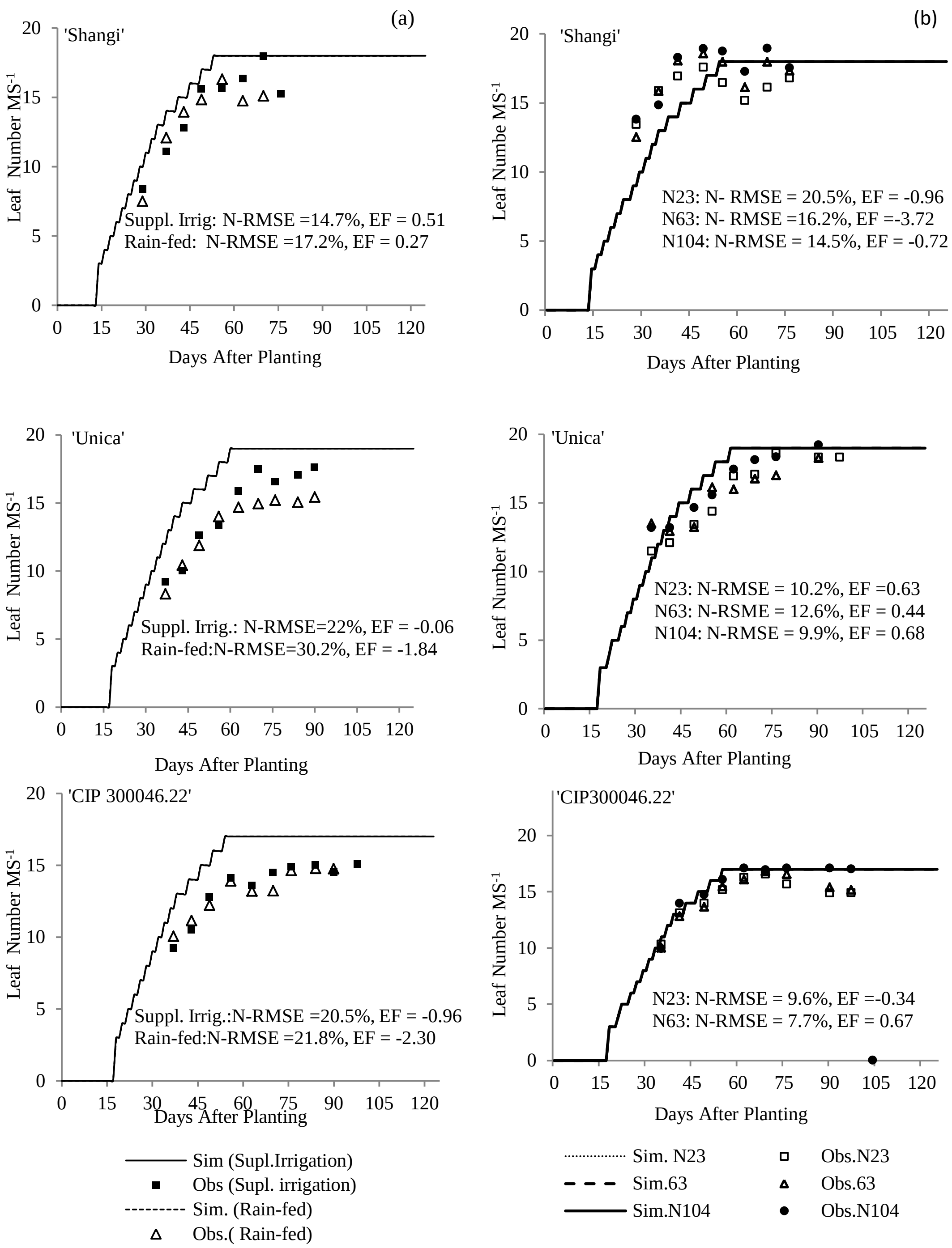

Figure 4.2 Change in observed and simulated number of leaves appearing on each main stem (MS) over time for ‘Shangi’, ‘Unica’ and CIP30046.22 grown during the SR2013 (a) and LR 2014 (b).

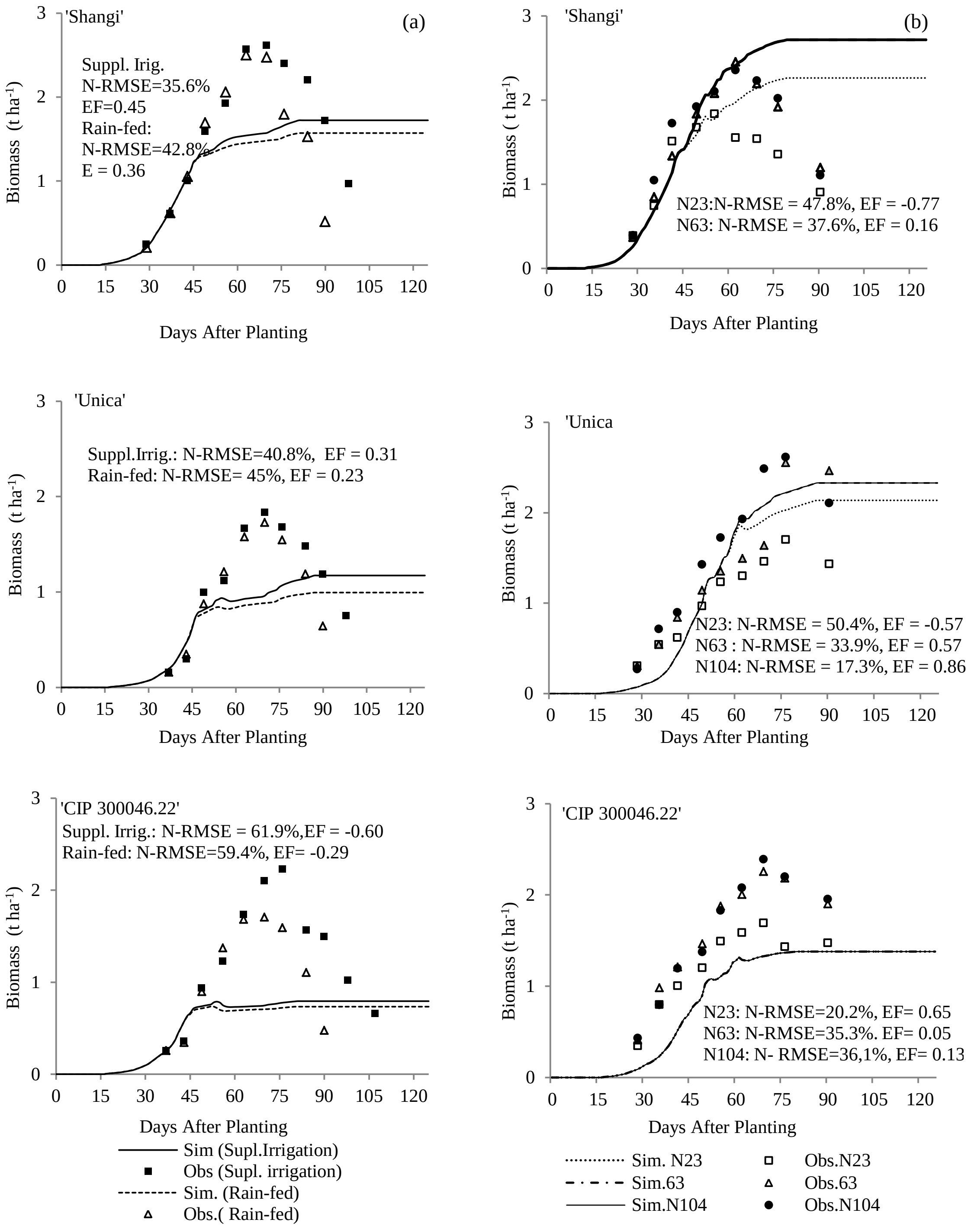

Figure 4.3 Change in observed and simulated aboveground biomass (t ha^{-1}) over time for ‘Shangi’, ‘Unica’ and ‘CIP30046.22’ grown during the SR2013 (a) season under rain-fed conditions and with supplementary irrigation and in the LR2014 (b) under three nitrogen levels. N23: 23 kg N ha^{-1}, N63: 63 kg N ha^{-1}, N104: 104 kg N ha^{-1}.

Tuber yield

For both seasons and all the genotypes and treatments, the model captured well the growth pattern and tuber partitioning over time (Fig.4.4). For SR2013, the index of agreement between simulated and observed values varied with genotype and water level but overall it was good (Table 4.7): N-RMSE = 24.9%, and EF = 0.9 for ‘Shangi’ N-RMSE = 10.8%, and EF = 1.0 for ‘Unica’, and N-RMSE = 20.5%, and EF = 1.0 for CIP 300046.22 across water levels in the SR2013 experiment. For LR2014, the simulation was also good, though inferior to the results for SR2013: N-RMSE = 29.3% and EF = 0.9 for ‘Shangi’, N-RMSE = 30.2% and EF = 0.9 for ‘Unica’, and N-RMSE = 26.1% and EF = 0.9 for CIP 300046.22 across the nitrogen levels.

Table 4.7 Simulated and observed end-of- season tuber dry matter (TDM) yield (t ha^{-1}) for the three genotypes grown during the SR2013 and LR2014 cropping season. Observed values are mean ±SE (n = 4). W: water, N: nitrogen.

	SR2013					**LR2014**					
W-level	Suppl. Irrigated		Rain-fed		N-level	N23		N63		N104	
Genotype	Sim.	Obs.	Sim.	Obs.	Genotype	Sim.	Obs.	Sim.	Obs.	Sim.	Obs.
‘Shangi’	6.5	5.8 ±0.14	4.6	3.7±0.16	Shangi	6.3	6.9 ±0.42	6.5	7.2 ±0.29	6.5	7.5±0.34
‘Unica’	6.3	6.2 ±0.29	4.4	3.9 ±0.15	Unica	6.6	7.0 ±0.26	6.6	8.8 ±0.67	6.6	9.2 ±0.37
CIP 300046.22	5.8	6.6 ±0.28	4.3	3.8 ±0.08	Clone	6.4	7.0 ±0.48	6.4	7.9 ±0.40	6.4	7.9 ±0.39
Mean	6.2	6.2 ±0.23	4.4	3.8 ±0.13	Mean	6.4	6.9 ±0.39	6.5	7.9 ±0.45	6.5	8.2 ±0.37

For both seasons and treatments, simulated values fitted well graphically with observed values but with cultivar variation (Fig.4.4). In the SR2013 experiment, the simulated values were marginally higher or equal to the observed values throughout the growing period for ‘Shangi’. For ‘Unica’ simulated values were equal to the observed values throughout the growing period and for CIP 300046.22, simulated values were higher during the first half of the growth stages but equal or lower in the later stages. In the

LR2014 experiment, simulated values were slightly higher or equal to the observed values during the first half of the growth stages (up to ~ 75 DAP) and then lower than the observed values in the latter growth stages for ‘Unica’ and CIP 300046.22 (Fig.4.4). For ‘Shangi’, there was a distinct bias towards higher observed values throughout the growing season. Given that ‘Shangi’ has a much shorter growth cycle and a faster growth and bulking rate compared to ‘Unica’ and CIP 300046.22, the difference in the simulated values are not surprising.

Despite the discrepancies in the time course, the model realistically reproduced the observed end-of-season tuber dry matter (TDM) yields for all the three genotypes investigated (Table 4.7). In the SR2013, the simulated TDM yields for the crop under rain-fed conditions averaged 4.4 t ha^{-1} and with supplementary irrigation TDM yields averaged 6.2 t ha^{-1} across genotypes which compares fairly well with observed values of 3.8 (± 0.13) and 6.2 (± 0.23) t ha^{-1} respectively. Furthermore, the model captured the effect of water level on TDM yields with supplementary irrigated fields giving higher TDM yields than the crop under rain-fed conditions.

At the experimental site, water level had significant effect on tuber yields as shown in Table 4.5. Similarly, the model realistically reproduced the observed TDM yields for all the three genotypes studied in the LR2014 experiment. The measured TDM yields in the LR2014 experiment averaged 7.2 (±0.35), 8.3 (±0.44), and 7.6 (±0.42) t ha^{-1} for ‘Shangi’, ‘Unica’ for CIP 300046.22 across the nitrogen levels compared simulated values of 6.4, 6.6 and 6.4 t ha^{-1} respectively. Nonetheless, the model did not fully capture the effect of nitrogen as it gave similar or marginally higher values for N104 nitrogen level compared to N63 and N23 nitrogen level (Table 4.7). Nitrogen had significant effect on final tuber yield and the marketable yield in the observed data as shown in Table 4.6.

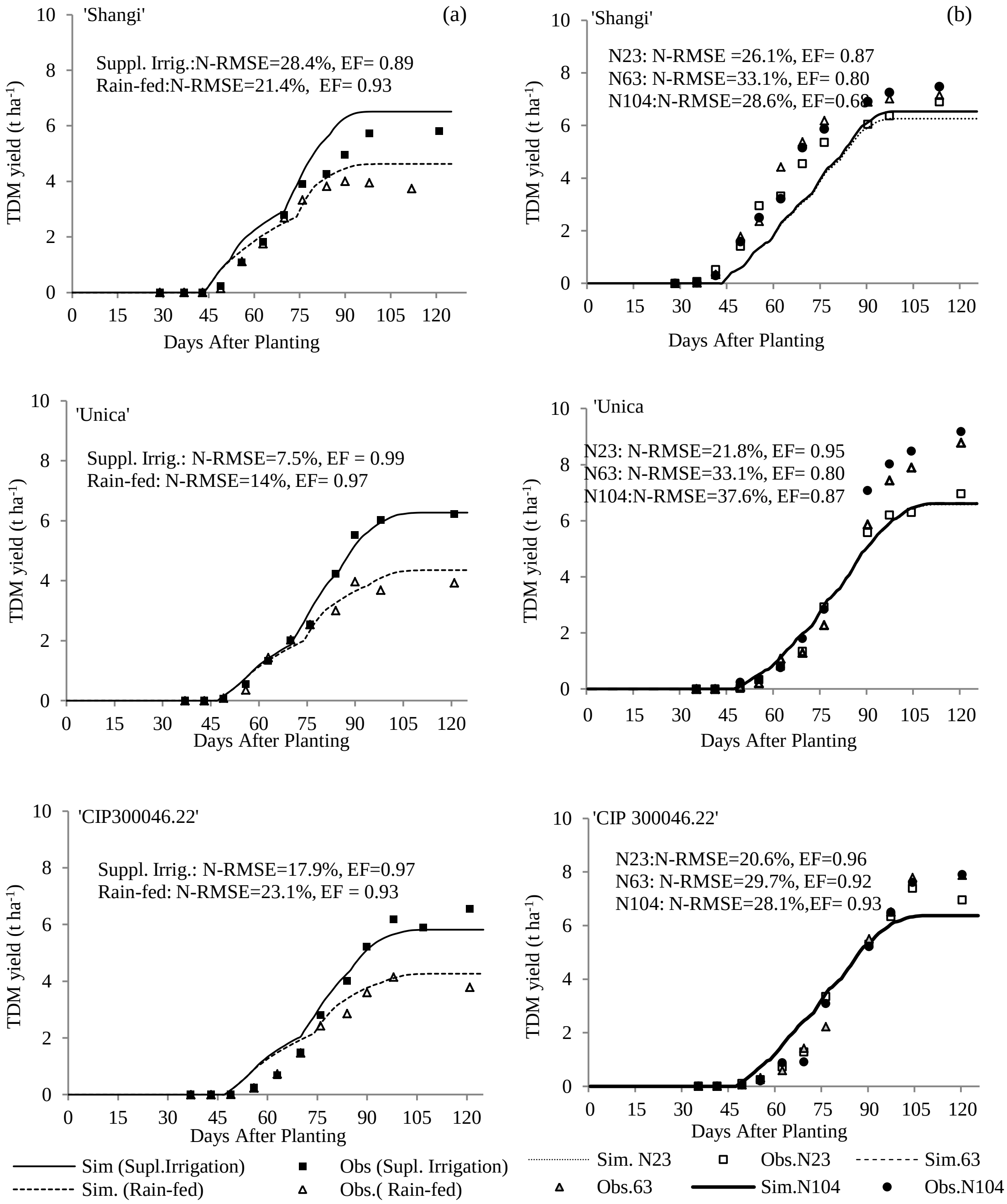

Figure 4.4 Change in observed and simulated tuber dry matter (TDM) yield (t ha^{-1}) over time for the three genotypes grown during the SR2013 (a) season under rain-fed conditions and with supplementary irrigation and in the LR2014 (b) under three nitrogen levels. N23: 23 kg N ha^{-1}, N63: 63 kgN ha^{-1}, N104: 104 kg N ha^{-1}.

Discussion

Graphically, the model realistically captured the partitioning of assimilates to the tuber state variable over time, with good indices of agreement for both seasons. Further, the model reasonably reproduced the observed end-of season TDM yields. Model predictions indicate that under rain-fed conditions, distribution of rainfall as well as the amount determines the final tuber yield. While all the six stages are sensitive to water stress, tuber initiation and tuber bulking are the most sensitive growth stages (MacKerron & Jefferies 1988; Haverkort 1990; Yuan et al. 2003).

Tuber yields and quality are adversely affected even by relatively mild water stress (Onder et al. 2005) and thus both simulated and observed tuber yields presented in this study are much lower than the potential tuber yield for each cultivar studied. There was moisture stress in both seasons as indicated by simulated water stress factors with more stress experienced in the SR2013 crop. The model realistically predicted lower tuber yield during the SR2013 experiment compared to LR2014, even though total rainfall received in the SR2013 cropping season was higher than the amount received during the LR2014 cropping season. The substantial amount of water stored in the soil at the start of the growing season and good crop establishment may have contributed to higher yields in LR2014 as well as the distribution of in-crop rainfall.

Notably, the model captured the significant effect of supplementary irrigation on biomass and tuber yield across the genotypes observed during the SR2013 cropping season. Introduction of supplementary irrigation was necessary to improve tuberization and tuber bulking. Although detailed data are not shown in this paper, the simulated water stress factor (fw) values simulated during tuber initiation and tuber bulking, the most sensitive growth stages range from 0.09 to 0.42 with the supplementary irrigated crop and from 0.00 to 0.33 in the rain-fed crop which shows that the model captures well the effect of supplementary irrigation. APSIM simulates crop water stress using the ratio of soil water supply to potential water demand with a value of 1.0 indicating no water stress and the lower the values, the more the water stress factor (Lobell et al. 2015).

Effect of nitrogen in the LR2014 experiment was poorly simulated with the model predicting similar or marginally higher TDM yields for N104 nitrogen level compared to N63 and N23 nitrogen level yet nitrogen had significant effect ($P = 0.0001$) on the observed final tuber yield (Table 4.6). Simulated nitrogen stress factor (fn) values for tuber initiation and bulking phenological stages were similar across the nitrogen levels (0.0 to 0.85) an indication that the crops experienced equal levels of nitrogen stress.

Relative to TDM yields, aboveground biomass was poorly simulated in both seasons. The simulation results are not atypical of crop modelling results based on previous studies. For example, Asseng et al. (1998) reported an excellent simulation for wheat grain yield and phenology but poor LAI prediction using APSIM-wheat. Nemecek (1996) reported a good agreement for tuber dry matter yield and leaf biomass but poor fit for stem biomass with 'Johnson'potato model. Wolf and Van Oijen (2003) observed a good prediction of tuber dry matter yield using LPOTCO-potato in half of the experimental sites but poor prediction in the remaining half of the experimental locations. Raymundo et al. (2017) reported good agreement between simulated and observed data for tuber yield in a majority of the sites when using SUBSTOR-potato model to simulate yield parameters and end of season tuber yield with data from 87 field experiments obtained from 19 countries. However, simulation results for both LAI and tuber N uptake sometimes differed from the measured values. The results presented in this paper provide an initial database on testing of the model and will guide future users to further improve the model. Further refining of the model will require collection of more long term field crop data which is beyond the scope of this research.

Considering that APSIM-potato is a fairly new model (Brown et al. 2011) compared to other APSIM plant models and that this is the first time it has been tested under tropical and suboptimal harsh conditions, the simulation results are promising. The majority of the other potato models have not been evaluated under high temperature, water or heat stress conditions (Boote et al. 2010; Raymundo et al. 2014) and by testing the model under Kenyan conditions, this study pioneered the testing of APSIM-potato in less favourable growing conditions. Since poor simulation of the aboveground biomass did not affect the accuracy in which the model simulated TDM yield and that biomass has no economic implications, APSIM-potato has potential for realistic simulation of the tuber organ, the economic yield of the potato.

Conclusion

Although the APSIM-potato model was developed for a temperate climate and parameterised with a long day cultivar, it reasonably simulated the growth pattern of short day cultivars and realistically reproduced observed TDM yield under tropical highland conditions in Kenya. The current limitations of the model are poor simulation of aboveground biomass. The model needs to be further refined and tested under potato growing tropical conditions within or outside Kenya and with short day cultivars. But we are confident in the model's ability to adequately predict tuber yields and in its potential to investigate the effects of climate change on potato productivity in Kenya.

To improve simulations under suboptimal tropical conditions, drought induced branch mortality and drought induced senescence accelerator, the two crop parameters, which are currently constant, should be adjusted in order for the model to capture accelerated senescence, as drought is a common occurrence under tropical rain-fed conditions. Both crop parameters have not been adjusted as the model has only been tested under un-limiting growth conditions in temperate regions.

Acknowledgements

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Chapter 5 : Potential impacts of climate change on potato productivity in contrasting environments: implications to crop management and policy

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Abstract

The net impacts of climate change on potato production remains largely un-researched both in Tasmania and in Kenya. This paper simulated potential tuber yield by 2050 and 2085 using projected climate data under the A2 emission scenario in Tasmania, Australia and Representative Concentration Pathway (RCP8.5) in Kenya. We used climate projections from the Climate Futures Tasmania project for Tasmania and an ensemble of climate projections under the CORDEX–Africa initiative for Kenya. Three study sites in Tasmania (Forthside, Cressy and Scottsdale) and two (Kabete and Bomet) in Kenya were chosen to represent distinct climatic conditions and soil types across the potato growing regions. The APSIM-potato model was used to run the simulations in both Countries. In Tasmania, simulation results indicate that tuber yield for 'Russet Burbank' will remain unchanged throughout the century although we report that there is a steady projected increase in GDD and hence earlier harvesting by up to 15 days across the three study sites. Projected tuber yield of 'Shangi' in

Kenya varied with location and cropping season with a projected increase of 11% by mid-century and 15% by 2100 in Kabete, while at Bomet, tuber yields are projected to increase by 29% and 31% respectively. Our results indicate that as temperature and atmospheric CO_2 increases, the interaction between these factors along with rainfall determines tuber yield in rain-fed conditions. If the temperatures are within the optimum range or potato plants are exposed to short-term period of high temperatures, tuber yields are driven by rainfall amount and distribution. Poor annual rainfall distribution had a strong effect where low yields were simulated; this was also evident in years with high annual rainfall. The impact of which is that potato farmers in Kenya, especially in Kabete is that development of irrigation systems to optimise and stabilise tuber yields should be implemented.

Keywords: APSIM-potato, climate change, climate scenario, tuber yield, food security, Tasmania, Kenya

Introduction

Elevated temperatures pose a serious threat to the production of potato (*Solanum tuberosum* L) given that it is a cool weather crop and drought sensitive (Van Loon 1981; Gregory & Simmonds 1992; Haverkort & Verhagen 2008; Fleisher et al. 2017). The crop is best grown in places where mean daily temperature are above 5 °C and below 21 °C (Haverkort and Verhagen 2008; Fageria et al. 2010). A daily mean temperature above 21 °C, is assumed to be too hot for potato growth. Tuberization is reduced by night temperatures of above 20 °C and the crop may fail to tuberize at night temperatures of 25 °C or above (Burton 1989). Further, potato is sensitive to water stress (both in adequate and excessive) and ample supply of water is needed throughout the growing season for good tuber yield and quality (Van Loon 1981; Gregory & Simmonds 1992; Fageria et al. 2010; Fleisher et al. 2013). Depending on the climatic conditions and the length of the growing season, potato requires 500 -700 mm of water for maximum yields (Gregory & Simmonds 1992; Lutaladio et al. 2009; Fageria et al. 2010).

Consequently, changes in temperature profiles have a strong impact on tuber yields (Schlenker & Lobell 2010). The level of effects of high temperature depends on the growth stage when high temperatures sets in with more negative impacts on growth and tuber yield when plants are exposed to heat stress at an earlier growth stage (Rykaczewska 2015). Conversely, increase in temperature may be beneficial to potato production in other regions (Hijmans 2003).

Without adaptation to a warming climate, global potato yields are projected to decrease by up to a third by 2050 (Hijmans 2003). climate, global potato yields are projected to decrease by up to a third by 2050 (Hijmans 2003). Out of the 27 potato producing countries considered, it is only in Bolivia where potato production would increase without adaptation and with adaptation an increase of 77% is predicted (Hijmans 2003. For any one region, however the impact of climate change on potato production will be the result of complex interactions and not necessarily negative (Hijmans 2003; Ebi et al. 2011; Saue & Kadaja 2011; Supit et al. 2012; Kumar et al. 2015). Data from Zhou et al. (2017) indicate a reduction in tuber dry matter by approximately 10% per °C as a result of reduction in radiation use efficiency at higher temperatures. When exposed to a range of day and night temperatures, maximum individual leaf area values were highest at cooler temperatures, (12-18 °C mean temperature) compared to high temperatures of above 20 °C (Fleisher et al. 2013). A warmer climate will have detrimental effect on potato with yield declining by an average of 50%, (Resop et al. 2016).

Conversely, increased temperatures may provide more favourable growing conditions and reduce frost damage or allow winter cropping (Holden & Brereton 2006; Haverkort 2007; Saue & Kadaja 2011). Earlier planting may allow crops to escape biotic damage for diseases and pests that build up during the rotation such as late blight and Colorado potato beetle (Pulatov et al. 2015). In recent years, many countries have been experiencing changes in the onset and duration of rainy seasons (Hijmans 2003; Funk et al. 2008; Lobell et al. 2008; Corney et al. 2010; Ebi et al. 2011; Saue & Kadaja 2011; Niang et al. 2014; Omondi et al. 2014; Reisinger et al. 2014; Kumar et al. 2015). Traditional potato varieties require 500-700 mm of water for maximum yields and will produce lower yields under reduced soil moisture conditions (Gregory & Simmonds 1992; Lutaladio et al. 2009; Fageria et al. 2010).

The positive impacts of increasing atmospheric CO_2 concentration on potato growth and development are well-documented (Miglietta et al. 1998; Kundzewicz et al. 2008; Kumari et al. 2015; Fleisher et al. 2017). Potato tuber yield also increase under elevated CO_2, reliant on CO_2 concentrations and nutritional and water limitations (Miglietta et al. 1998). Under two management levels (low and high-inputs), tuber yield increased by 6% per 100 ppm increase in CO_2 levels with more variation in low-input systems (Fleisher et al. 2017). At higher CO_2 concentrations, leaf photosynthetic water use efficiency (WUE) is enhanced resulting in greater net photosynthesis (Kaminski et al. 2014). A reduction in stomatal conductance under elevated CO_2 will reduce water use (Hijmans 2003; Lobell et al. 2015).

In Tasmania (Australia), climate change projections under a high emission scenario (A2) indicate that the seasonal and regional distribution of rainfall will change (although the mean annual amounts will not vary significantly) along with projected increases in maximum and minimum temperatures of up to 2.9 °C by 2100 (Corney et al. 2010). The impact of climate change on Tasmania may not be as detrimental as continental Australia, and may offer opportunities for agriculture if the availability and cost of irrigation water is not limiting (Holz et al. 2010).

In some locations, frost occurences are projected to reduce by up to 50%, while an increase is projected in accumulation rate of growing degree-days (GDD) resulting in some crops (e.g wheat and barley) maturing one to two months earlier by 2100 (Holz et al. 2010). Further, this may allow the opportunity of growing crops in new regions which were previously temperature limited e.g. wheat, canola, grapes, etc (Holz et al. 2010). Phelan et al. (2014) and Holz et al. (2010) analysed the impact of various climate change scenarios on several crops (wheat, vines, pastures) throughout regional Tasmania, however potatoes were not incorporated in their respective studies.

In Kenya, the highland areas are the agricultural breadbasket of the country. These areas have already shown an increase in the frequency of warm nights and days over the period 1961 to 1990, a trend which is projected to continue (Omondi et al. 2014). In Eastern Africa, rainfall is projected to increase throughout the rainy season interspersed by months with less rainfall (Lobell et al. 2008; Niang et al. 2014). However, observed trends shows a drier rainy season in Eastern Africa (Funk et al. 2008) and an overall decrease in total rainfall for the period 1971 to 2006 in the Greater Horn of Africa (Omondi et al. 2014). Numerous climate impact studies on agricultural crops have been conducted both in Eastern Africa and in Kenya (Thornton et al. 2010; Adhikari et al. 2015; Barasa et al. 2015; Omoyo et al. 2015; Thornton & Herrero 2015), although climate impacts on the potato crop were not included in their respective studies.

In Tasmania, the potato crop is the mainstay of the vegetable industry representing up to 70% of the industry and 9% of State's agricultural total value (DPIPWE 2014). Potato production in Tasmania is highly intensive and irrigation-dependent. The crop is planted between mid-spring and early summer (September - December) and approximately 500 mm of water is applied during the growing season. Many households in Kenya are reliant on the potato crop as a source of food and nutrition as well as income generation (Kaguongo et al. 2013). Throughout Kenya, potatoes are predominantly grown under rain-fed conditions in medium to high altitude areas between 1500 and 3000 AMSL (above mean sea level) with cool weather conditions. Potatoes are planted twice in a year: during the March-April-May (MAM) or "Long Rains" (LR), and October-November-December (OND) also known as the "Short Rains" (SR). In contrast to major cereals (wheat, rice and maize), the potato has not received much interest in climate impact studies (White et al. 2011).

This paper investigates the potential impacts of projected climate change on potato production in Kenya and Tasmania and provides two very different potato production systems and climate change scenarios for comparison. It is the first study to apply the recently developed APSIM-potato model (Brown et al. 2011) to quantify climate change impacts on potato production. As reported in Chapter 3 and 4 of this study, APSIM-potato has been parameterised under both Tasmanian and Kenyan potato growing conditions. The projected climate data was sourced from Climate Futures Tasmania (CFT) (Corney et al. 2010) while high-resolution climate data were generated specifically for the Kenyan study sites under the CORDEX Africa Initiative (Moss et al. 2010; Van Vuuren et al. 2011; Nikulin et al. 2012).

Materials and Methods

Study sites

Three study sites, Forthside, Cressy and Scottsdale, were selected to represent major potato-growing regions of Tasmania i.e. north west, central north and north east Tasmania (Table 5.1). The dominant soils in Forthside is Red Ferrosol and Brown Dermasol in Scottsdale and Dermasol. In Kenya, two study sites representing potato growing counties were selected, Bomet and Kabete (Table 5.1, Fig. 5.1). Bomet is a renowned production area for processing potatoes at high altitude (>2000 AMSL) with high rainfall and production all year round. Kabete is a mid-altitude (1500 - 2000 AMSL) region. The predominant soils in Kabete is Nitisol and Andosol in Bomet (Nyandat 1977).

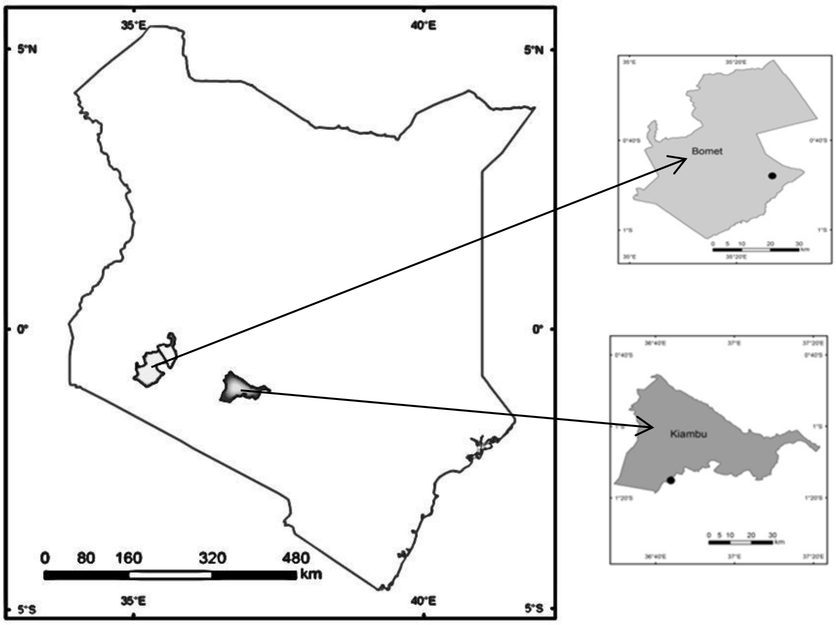

Figure 5.1 Map of Tasmania, Australia, showing the location of the three study sites (Cressy, Forthside and Scottsdale) (Top). Map of Kenya showing the location of the two study sites (Bomet and Kabete) (Bottom). The dots in the Kenyan map indicate locations where crop or soil data were measured. It also represents the grid cell from which future data were generated under the CORDEX- Africa initiative (bottom).

Table 5.1 Coordinates, elevation (AMSL) and multi-model mean annual daily maximum (Tmax) and minimum (Tmin) temperature, mean annual rainfall, and mean annual daily solar radiation for the baseline (1981-2010), projected mean annual maximum and minimum temperature change, mean annual rainfall percentage change, and mean annual solar radiation percentage change for 2050 and 2085 at five study sites both in Tasmania and Kenya.

Site/GCM	**Lat., Long**	**Alt**	**Baseline**				**2050s**				**2085**			
		(m)	Tmax (ºC)	Tmin (ºC)	Rainfall mm/ yr	Radn MJ^{-2}/day	Tmax ΔºC	Tmin ΔºC	Rainfall %Δ	Radn %Δ	Tmax ΔºC	Tmin ΔºC	Rainfall %Δ	Radn %Δ
Cressy	-41.60, 147.00	162	17.5	6	745.8	15.3	1.2	1.4	2.2	-0.1	2.4	2.7	6.1	-0.1
Forthside	-41.00, 146.26	125	17.1	8.1	915.1	17.5	1.2	1.3	1.4	0	2.4	2.5	4.5	0
Scottsdale	-42.1, 147.52	225	17.7	8.3	858.2	17.3	1.2	1.4	3.7	-0.1	2.5	2.7	9	-0.1
Bomet	-0.79, 35.45	2298	22	12.2	2353.4	21.7	0.6	1.3	-46.1	1	2.3	3.1	-42.3	0.6
Kabete	-1.25, 36.73	1840	26.5	16.1	1080.1	25.3	2.4	2.6	1.6	-0.2	4.1	4.4	15.9	-0.2

Soil data

For the study sites in Kenya (Kabete and Bomet), measured soil data (physical, chemical and hydraulic properties) (Table 5.2) were used to initialize the APSIM-potato simulations. For the Tasmanian sites, soil data used to run the simulations were selected from the APSoil database (Table 5.2) Brown Dermosol for Scottsdale, Red Ferrosol for Forthside and Dermosol for Cressy.

Crop data and management events

In Tasmania, we used ‘Russet Burbank’, a long-day late maturing cultivar with tuber initiation and canopy development taking place over a relatively longer period (Beattie 2010). ‘Shangi’, a short-day, early maturing cultivar was used in Kenya. Preceding this study, we conducted an experiment at Forthside, North-West Tasmania during the 2012/2013 cropping season and at Kabete farm, Kenya during the SR2013 and LR2014 (refer to Chapter 3 and 4) and the crop data and management events (Table 5.3) collected at the experimental sites were used to initialise APSIM-potato simulations.

Table 5.2 Soil chemical, physical and soil hydraulic properties used as input parameter data to run the simulations at each of the study sites both in Tasmania and in Kenya.

Depth cm	**BD gcc^{-1}**	**Air dry**	**LL15**	**DUL**	**SAT**	**EC dSm^{-1}**	**Depth cm**	**OC %**	**pH**	**NO3-N ppm**	**NH4-N**
			mm mm^{-1}								
Cressy (Dermosol, APSIM No.660)											
0-20	1.32	0.07	0.14	0.40	0.50	0.09	0-15	1.86	5.00	10.60	6.29
20-32	1.43	0.12	0.16	0.42	0.46	0.09	15-30	1.48	5.00	11.50	6.91
32-50	1.43	0.16	0.16	0.42	0.46	0.09	30-60	1.12	5.00	8.59	6.74
50-105	2.04	0.12	0.12	0.22	0.23	0.09	60-90	0.46	5.00	3.09	2.43
105-140	1.93	0.21	0.21	0.26	0.27	0.09					
Forthside (Red Ferrosol, APSIM No.776)											
0-21	1.11	0.14	0.28	0.44	0.55	0.14	0-15	3.32	6.58	24.00	10.80
21-40	1.21	0.23	0.29	0.41	0.51	0.12	15-30	1.93	6.52	12.80	9.20
40-65	1.21	0.29	0.29	0.41	0.51	0.12	30-60	1.73	6.50	10.20	8.58
65-93	1.21	0.30	0.30	0.41	0.51	0.12	60-90	0.54	6.50	0.39	0.03
93-120	1.20	0.34	0.34	0.47	0.52	0.12					
Scottsdale (Brown Dermosol, APSIM No. 780)											
0-13	1.40	0.09	0.19	0.39	0.44	0.09	0-15	2.30	7.30	7.17	8.61
13-26	1.48	0.18	0.22	0.36	0.41	0.06	15-30	1.76	6.20	7.16	8.00
26-48	1.63	0.25	0.25	0.31	0.36	0.06	30-60	0.19	6.50	4.58	8.15
48-80	1.34	0.25	0.25	0.41	0.46	0.07	60-90	0.36	6.20		
80-100	1.51	0.35	0.35	0.35	0.40	0.05					
Kabete (Nitisol, measured data)											
0-21	1.01	0.20	0.22	0.29	0.46	0.15	0-15	2.25	6.4	8.428	12.04
21-40	1.14	0.26	0.26	0.33	0.47	0.10	15-30	1.93	5.8	6.02	7.224
40-65	1.12	0.26	0.26	0.34	0.49	0.15	30-60	1.83	6.5	1.204	6.541
65-105	1.16	0.27	0.27	0.34	0.47	0.10					
105-140	1.00	0.23	0.23	0.34	0.48	0.10					
Bomet (Andosol, measured data)											
0-20	1.07	0.20	0.28	0.39	0.47	0.15	0-15	2.76	5.16	31.26	45.24
21-45	0.94	0.26	0.26	0.41	0.51	0.10	15-30	1.76	5.78	21.56	36.64
46-65	0.98	0.26	0.26	0.42	0.51	0.10	30-45	1.17	5.58	17.64	38.40
66-85	0.91	0.25	0.25	0.41	0.52	0.13	45-60	0.42	5.61	14.60	25.20
86-110	0.92	0.24	0.24	0.41	0.53	0.10					

BD: bulk density, LL15: crop lower limit, DUL: drained upper limit, SAT: plant available water content at saturation, NO3- N: Nitrate nitrogen, NH4+: Ammonium nitrogen, EC: Electrical conductivity, OC: Organic Carbon.

Table 5.3 Crop and management as input parameters to initialise APSIM-potato simulations.

Events	**Tasmania**	**Kenya**			
	Cressy, Forthside, Scottsdale	**Bomet SR**	**LR**	**Kabete SR**	**LR**
Cultivar	'Russet Burbank'	'Shangi'		'Shangi'	
Reset planting date	15th Oct	5th Oct	3rd March	5th Oct	4th April
Sowing depth (mm)	150	150	150	150	150
Row spacing (mm)	810	750	750	750	750
Inter row (mm)	300	300	300	300	300
No. of MS plant^{-1}	2.0	3.0	3.0	3.0	3.0
N-application (Kg N ha^{-1})	320	90	90	90	90

LR: Long rains, SR: Short rains, MS: Main stem

Climate data

High-resolution (0.1 degrees) daily climate data for maximum and minimum temperature (°C), rainfall (mm) and solar radiation ((MJ/m^2.day) for the period 1st January 1961 to 31 December 2100 were obtained from the Tasmanian Partnership for Advanced Computing (TPAC) portal (https://dl.tpac.org.au). The Climate Futures Tasmania (CFT) project generated the detailed future climate scenarios for Tasmania using six general circulation models (GCMs). CFT used five out of the 23 GCMs used in the Fourth Assessment Report (AR4), (IPCC 2007) and a sixth model, the CSIRO-MK3.5 (Corney et al. 2010). The six GCMs (CSIRO-MK3.5, ECHAM5/MPI-OM, GFDL-CM2.0, GFDL-CM2.1, MIROC3.2 (medres), and UKMO-HadCM) were selected on objective metrics of the skill of each model in simulating the climate over south-east Australia (Corney et al. 2010). Each individual GCM output included approximately 140 variables at six-hourly and daily time steps for the period 1961 to 2100 (Corney et al. 2010). Any bias in temperature or rainfall may significantly affect GCM outputs. Intrinsic biases in climate models can be managed by perturbing historical datasets with projected anomalies or by correcting the climate model outputs (Bennett et al. 2014).

For the three sites in Tasmania, a 30 year baseline was selected from 1981 to 2010, additionally two 30-year climate periods were selected: 2050 (2036-2065) and 2085 (2071-2100) under the A2 emission scenario, a high-emission scenario from the Special Report on Emissions Scenarios (SRES). SREs used in the IPCC Fourth Assessment Report (AR4) (Nakicenovic & Swart 2000) describes the possible range of future climates based on the rate of population change, economic and technological development and atmospheric CO_2 concentration as the key features. A2, represents the worst case scenario and describes a future heterogeneous world with CO_2 emission predicted to increase by 4 to 5 fold (from 369 to 850 ppm) over the 2000-2099 period with the best temperature estimate of 3.4 °C (likely range is 2.0 °C to 5.4 °C).

For Kenya, daily climate data (maximum and minimum temperature, rainfall and solar radiation) was used from the Coordinated Regional Downscaling Experiment (CORDEX-Africa) for the period 1st January 1961 to 31 December 2100 (Nikulin et al. 2012). Under the CODREX-Africa initiative, a high-resolution projected data set over Africa at a spatial resolution of approximately 50 km (0.5°) for reference concentration pathways RCP4.5 and RCP8.5 were available (Moss et al. 2010; Van Vuuren et al. 2011). A baseline of 30 years was selected, for the period 1961 to 1990, additionally two future climate periods were selected: 2050 (2036-2065) and 2085 (2071-2100) for Reference Concentration Pathways, RCP8.5 (IPCC 2013). RCPs 4.5 and 8.5 are roughly analogous to the SRES B1 and A1B (Giorgi & Gutowski 2015). RCP8.5 used for simulation in Tasmania and A2 emission scenario used for the simulation in Kenya represent the high-end of RCPs and SRES respectively. However, RCPs and SRES are different (Rogelj et al. 2012) and hence RCP8.5 is different from A2.

Projected climate trends in the potato growing regions

The mean monthly and annual values for each 30-year period were calculated for the four climate variables across Tasmania. Trends in maximum and minimum temperature, and solar radiation were generally consistent between the models, however, there were differing trends for rainfall (Fig 5.2a). The bias-adjusted gridded daily climate projections show that for each site, the observed increase in temperatures during the latter half of the 20th century are projected to continue into the 21st century. Multi-model mean annual daily maximum temperatures are projected to increase by 1.2 °C by 2050 and 2.4 to 2.5 °C by 2085 (Table 5.1) across each site. Multi-model mean annual daily minimum temperatures are projected to increase by 1.3 °C to 1.4 °C by 2050 and 2.5 °C to 2.7 °C by 2085 (Table 5.1 and 5.4).

Future mean annual rainfall at all locations is projected to increase above the baseline value ranging from 1% (Forthside) to 4% (Scottsdale) by 2050 and by 5% (Forthside) to 9% (Scottsdale) by 2085 (Table 5.1and 5.4). The mean annual rainfall projections of the six GCMs throughout the 21st century indicate slight increases for each site, particularly during the winter months (Fig. 5.2b). The absence of significant changes in projected annual rainfall trends is not unusual, considering that rainfall is not expected to respond as strongly to increases in greenhouse gas forcing as temperature variable (Alexander & Arblaster 2009).

The mean monthly and annual values for each 30-year period were calculated for the three climate variables across Kenyan sites. There was a marked variation between the models and between the two potato growing regions with the trend of the three climate variables (Tmax, Tmin and rainfall) and in particular rainfall (Table 5.1, 5.5 and Fig.5.3). At Bomet, reduction of multi-model monthly rainfall is projected for the months of April through to October with the highest reduction projected during the June-July-August (JJA) rainy season. An increase is projected for the remaining months with the highest increased projected for the months of November and December. At Kabete, multi-model monthly rainfall is projected to reduce during the months of May through to August and an increase is projected for the remaining months.

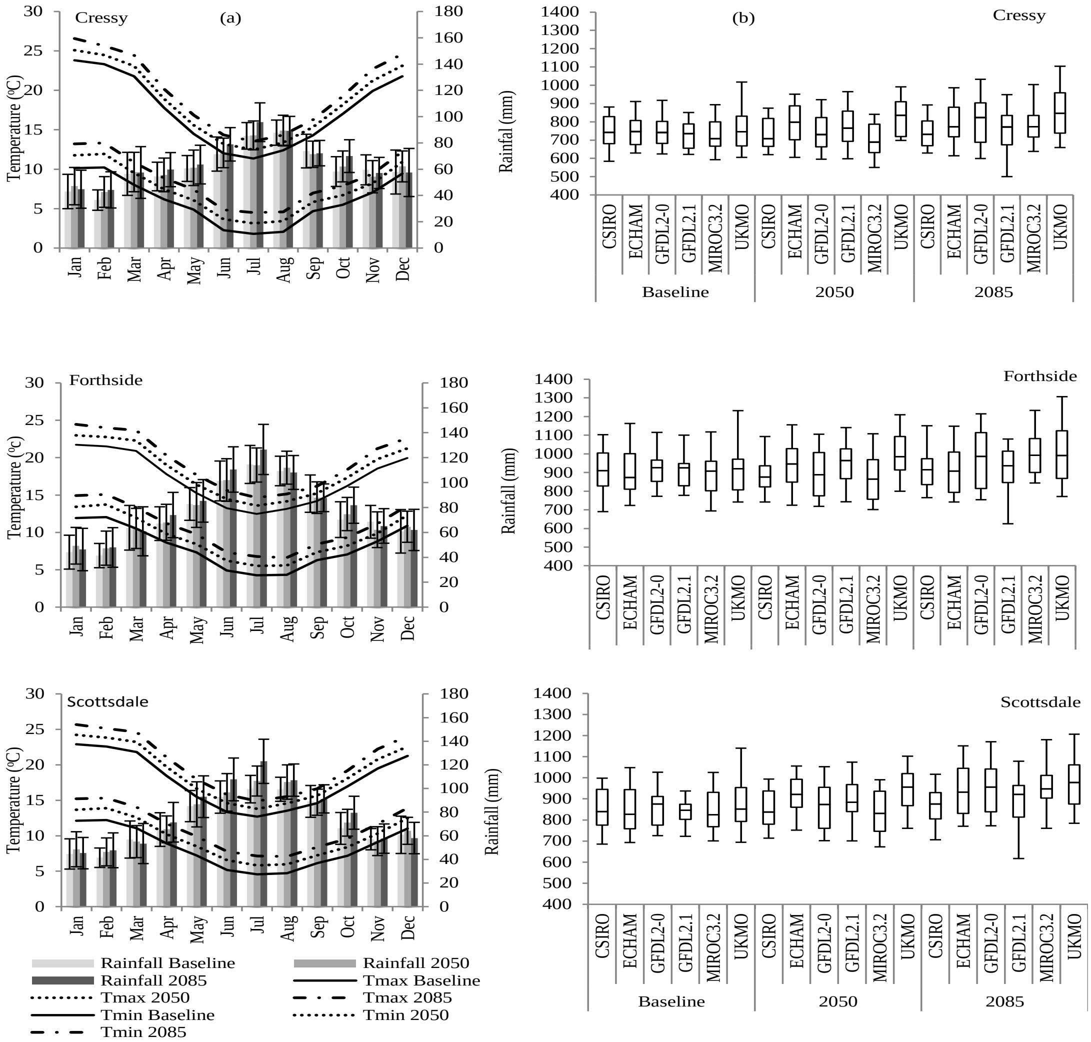

Figure 5.2 Multi-model mean monthly rainfall (mm) with errors bars (± SD, n=30) and maximum and minimum temperature (^{o}C) (a) and projected annual rainfall (mm) (b) per GCM for baseline period (1981-2010), 2050 and 2085 under A2 emissions scenario at Cressy, Forthside, and Scottsdale, Tasmania, Australia. The boxplot shows the 25, 50 and 75 percentile. The whiskers show 5% and 95% percentile.

The multi-model 30-year mean maximum and minimum temperature are projected to increase across the potato growing areas investigated (Table 5.1 and 5.5). The projected increase is higher at Kabete, the lower altitude region with a mean increase of a 2.4 °C (Tmax) and 2.6 (Tmin) by mid-century and 4.1 °C (Tmax) and 4.4 °C (Tmin) increase by 2085 compared to 0.6 °C (Tmax) and 1.3 °C (Tmin) by mid-century and 2.3 °C (Tmax) and 3.1 °C (Tmin) in Bomet (Table 5.1 and 5.5). Projected changes in multi-model 30-year mean rainfall are both site and seasonal specific, with a reduction at Bomet by 46.1% by 2050 and 42.3% by 2085 (Table 5.1, 5.5 and Fig. 5.3b). The opposite is projected at Kabete with a 1.6% increase in multi-model 30-year mean annual rainfall by 2050s and by 15.9% by 2085. In both sites, a reduction in multi-model mean rainfall is projected for LR (MAM) and an increase in rainfall is projected for SR (OND), (Table 5.7).

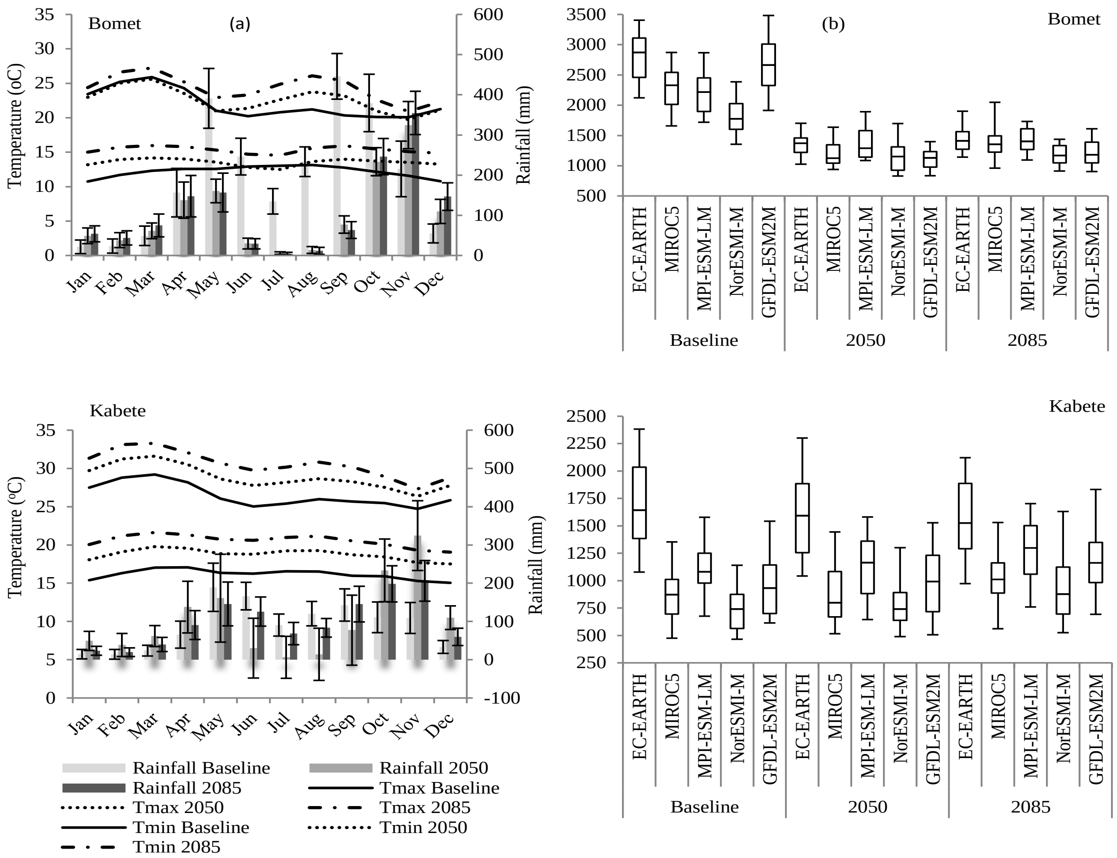

Figure 5.3 Multi-model mean monthly rainfall (mm) with errors bars (a) (± SD, n=30) and maximum and minimum temperature (°C) (a) and projected annual rainfall (mm) (b) per GCM, baseline period (1961-1990), 2050 and 2085 under RCP8.5 at Bomet and Kabete. The boxplot shows the 25, 50 and 75 percentile. The whiskers show 5% and 95% percentile.

Table 5.4. Climate data for the baseline (1981-2010) and projected changes in each of the climate variables for 2050 (2036-2065) and 2085 (2071-2100): mean minimum (Tmin) and maximum (Tmax) temperature, annual rainfall and solar radiation (Radn) generated from six GCMs for each of the study sites in Tasmania.

Site/GCM	Baseline				2050s				2085			
	Tmax (ºC)	Tmin (ºC)	Rainfall mm/ yr	Radn MJ^{-2}/day	Tmax ΔºC	Tmin ΔºC	Rainfall %Δ	Radn %Δ	Tmax ΔºC	Tmin ΔºC	Rainfall %Δ	Radn %Δ
Cressy												
CSIRO Mk 3-5	17.4	5.9	745	15.3	1.4	1.6	-1.4	0.0	2.9	3.2	0.0	0.0
ECHAM5	17.5	6.1	751	15.3	1.0	1.2	5.0	-0.1	2.2	2.4	4.5	0.0
GFDL2-0	17.4	6.0	752	15.3	1.0	1.1	-1.1	0.1	2.2	2.4	8.1	0.0
GFDL2-1	17.6	6.0	731	15.3	1.1	1.4	5.5	-0.1	2.2	2.4	2.8	0.0
MIROC3-2	17.4	5.9	728	15.4	1.2	1.4	-3.5	-0.1	2.4	2.7	8.1	-0.4
UKMO-HadCM3	17.5	6.1	767	15.4	1.3	1.6	8.9	-0.2	2.4	2.8	12.9	-0.2
MME	17.5	6.0	746	15.3	1.2	1.4	2.2	-0.1	2.4	2.7	6.1	-0.1
Forthside												
CSIRO Mk 3-5	17.0	8.0	911	17.5	1.4	1.5	-1.9	0.1	2.8	3.0	1.0	0.1
ECHAM5	17.1	8.2	917	17.5	1.0	1.1	3.3	0.0	2.3	2.3	-0.2	0.1
GFDL2-0	17.0	8.0	929	17.4	1.0	1.0	-3.3	0.1	2.2	2.2	4.7	0.1
GFDL2-1	17.1	8.1	914	17.6	1.1	1.3	4.1	-0.1	2.2	2.4	-0.4	0.0
MIROC3-2	17.0	8.0	892	17.6	1.2	1.3	-1.3	-0.1	2.3	2.6	13.0	-0.4
UKMO-HadCM3	17.1	8.1	928	17.6	1.4	1.6	7.1	-0.1	2.6	2.8	9.2	-0.1
MME	17.1	8.1	915	17.5	1.2	1.3	1.4	0.0	2.4	2.5	4.5	0.0
Scottsdale												
CSIRO Mk 3-5	17.7	8.2	855	17.2	1.4	1.6	-0.1	0.0	2.9	3.1	1.3	0.1
ECHAM5	17.8	8.4	857	17.3	1.1	1.2	8.4	0.0	2.4	2.5	11.1	0.1
GFDL2-0	17.7	8.2	869	17.2	1.0	1.1	-0.7	0.1	2.3	2.5	10.5	0.0
GFDL2-1	17.8	8.3	850	17.4	1.1	1.4	5.8	-0.2	2.2	2.5	4.2	-0.1
MIROC3-2	17.7	8.2	844	17.4	1.2	1.4	-0.3	-0.1	2.4	2.7	13.4	-0.4
UKMO-HadCM3	17.7	8.3	874	17.3	1.4	1.6	8.9	-0.1	2.6	2.8	13.2	-0.2
MME	17.7	8.3	858	17.3	1.2	1.4	3.7	-0.1	2.5	2.7	9.0	-0.1

MME: Multi model ensemble mean

Table 5.5 Climate data for the baseline (1961-1990) and projected changes in each of the climate variable for 2050 (2036-2065) and 2085 (2071-2100): mean minimum (Tmin) and maximum (Tmax) temperature, total annual rainfall and solar radiation (Radn) generated from five GCMs for the study sites in Kenya.

Site/GCM	Baseline				2050				2085			
	Tmax (ºC)	Tmin (ºC)	Rainfall mm/ yr	Radn MJ^{-2}/day	Tmax ΔºC	Tmin ΔºC	Rainfall %Δ	Radn %Δ	Tmax ΔºC	Tmin ΔºC	Rainfall %Δ	Radn %Δ
Bomet												
EC-EARTH	20.8	11.6	2795	20.9	0.9	1.1	-51.3	1.8	2.7	3.0	-48.3	1.4
MIROC 5	22.2	13.2	2285	21.5	0.6	0.8	-47.3	0.9	2.2	2.5	-39.1	0.5
MPI-ESM-LR	22.2	11.0	2208	22.1	0.5	2.7	-38.5	0.7	2.7	5.0	-35.0	0.1
NorESM1-M	23.1	13.1	1818	22.8	-0.1	0.8	-35.2	0.0	1.6	2.3	-35.8	-0.1
GFDL-ESM2M	21.6	12.0	2661	21.3	0.9	1.3	-58.1	1.5	2.4	2.8	-53.4	1.0
MME	22.0	12.2	2353	21.7	0.6	1.3	-46.1	1.0	2.3	3.1	-42.3	0.6
Kabete												
EC-EARTH	25.0	15.2	1707	24.1	2.4	2.4	-5.7	0.3	4.3	4.4	-8.8	0.3
MIROC 5	26.9	16.6	870	25.1	2.5	2.7	2.9	0.1	4.0	4.3	18.9	0.1
MPI-ESM-LR	26.7	16.4	1102	25.8	2.5	2.8	1.7	-0.8	4.5	4.9	15.5	-0.8
NorESM1-M	27.5	16.9	731	26.2	1.9	2.3	9.7	-0.4	3.5	3.9	32.8	-0.4
GFDL-ESM2M	26.2	15.6	992	25.5	2.6	2.8	-0.8	0.0	4.0	4.5	21.0	0.0
MME	26.5	16.1	1080	25.3	2.4	2.6	1.6	-0.2	4.1	4.4	15.9	-0.2

MME: Multi model ensemble mean

Climate variability

At all sites in Tasmania, the coefficient of variation (CV) of annual and seasonal rainfall is projected to increase from the baseline to 2085 (Table 5.6 and Fig. 5.4a). The CV increased by 2% at both Scottsdale and Forthside above the baseline value of 13% and 14% respectively and by 3% at Cressy above the baseline value of 14% (Table 5.6). It increased by 2% at both Cressy and Scottsdale and by 3% at Forthside for winter rainfall from a mean of 18% across the three sites. Projected increase of inter-model CV for summer ranged between 1 to 2%, 3 to 4% for spring and 2 to 4 % for autumn rainfall across the three sites.

Mean annual and seasonal rainfall intensity is projected to increase from the baseline to 2085 (Fig.5.4b). Annual rainfall intensity by 10% at Forthside and 12% at both Cressy and Scottsdale above the baseline value of 8.2 at Forthside, 7.3 at Cressy and 7.2 at Scottsdale (Fig.5.4b). The lowest change in seasonal rainfall intensity is projected to occur during summer while the highest increase is projected during spring with a mean increase of 3% and 17% respectively across the three sites by 2085 above the baseline. In contrast, the total annual and seasonal number of rain days with the exception of summer is projected to decrease from the baseline to 2085, by 6% at Cressy and 3% at Scottsdale for annual rainfall (Fig. 5.4b). Though marginally, the number of rain days during summer are projected to increase with a mean increase of 0.5% across the three sites by 2085 above the baseline. The inter-model range in the projected annual rainfall intensity showed that the MIROC3.2 (medres) GCM consistently projected rainfall intensity above the multi-model mean value at all sites

In Kenya, CV of annual maximum and minimum temperatures at both Bomet and Kabete are projected to decrease from the baseline to 2085 (by 0.8% and 0.6% at Bomet and Kabete above the baseline values of 4.1% and 3.7% respectively for maximum temperature; by 3%

and 0.5% at Bomet and Kabete above the baseline of 7.8% and 4.6% at respectively for minimum temperature) (data not shown).

There is a marked regional variability in rainfall (23% CV at Bomet and 43% in Kabete) at baseline with no clear trend throughout the century at each site (Table 5.7 and Fig. 5.5a). The CV of annual rainfall is projected to decrease from the baseline to 2085 at both sites. Similarly, there is inter-seasonal variability for both long rains (LR) and short rains (SR) with a projected reduction of CV of LR and SR rainfall at both sites (Table 5.7)

Projection for rainfall intensity and number of rain days varied with sites and season (Fig.5.5b). At Bomet, rainfall intensity is projected to decrease from the baseline to 2085 by 7% for SR, by 18% for annual rains and by 28% for LR below the baseline value of 14 both for annual and seasonal rainfall. In addition, the total number of rain days is projected to decrease by 30% (annual rainfall) and by 9% (LR) but an increase is projected for SR (25%) by 2085 from baseline values of 167, 39 and 44 days respectively. At Kabete, rainfall intensity and number of rain days are projected to increase (Fig.5.5b). Rainfall intensity is projected to increase from the baseline to 2085 by 1% for LR, by 7% for annual rainfall and 29% for SR by 2085. Total number of rain days is projected to increase by 4% (LR), 7% (annual rainfall) and 44% SLR) from baseline values of 23, 106 and 26 days respectively. The inter-model range in the projected annual rainfall intensity showed that the GFDL-ESM2M GCM projected the highest increase in rainfall intensity while NorESMI-M GCM projected the highest increase for the number of rain days at Kabete.

Table 5.6 Annual and seasonal variability in the projected multi-model 30 year mean rainfall for the baseline, 2050 and 2085 for Cressy, Forthside and Scottsdale under the A2 emission scenario. Baseline period is 1981-2010.

Site	**Period**	**Cv (%)**	**Stdev**	**Max**	**Min**	**mean**
		Annual rainfall				
Cressy	Baseline	14%	102	1109	557	745
	2050	15%	115	1113	523	762
	2085	17%	135	1322	468	790
Forthside	Baseline	14%	131	1338	650	915
	2050	15%	138	1397	679	928
	2085	16%	156	1562	525	957
Scottsdale	Baseline	13%	111	1259	649	858
	2050	14%	121	1239	640	890
	2085	15%	141	1574	588	935
		Winter rainfall				
Cressy	Baseline	19%	46	387	123	245
	2050	20%	49	382	148	247
	2085	20%	54	441	129	264
Forthside	Baseline	18%	57	476	175	325
	2050	20%	65	527	194	328
	2085	21%	71	571	173	345
Scottsdale	Baseline	19%	54	480	155	292
	2050	21%	64	493	181	309
	2085	21%	71	635	191	338
		Autumn rainfall				
Cressy	Baseline	30%	52	344	70	171
	2050	32%	56	378	73	175
	2085	34%	62	500	56	181
Forthside	Baseline	31%	65	445	83	214
	2050	33%	70	438	66	213
	2085	33%	72	421	53	220
Scottsdale	Baseline	28%	59	420	95	207
	2050	31%	64	480	97	207
	2085	31%	67	389	57	218
		Spring rainfall				
Cressy	Baseline	26%	50	341	98	191
	2050	25%	48	368	90	188
	2085	30%	60	368	71	199
Forthside	Baseline	29%	66	482	96	230
	2050	26%	58	399	98	225
	2085	32%	74	548	91	235
Scottsdale	Baseline	26%	55	405	115	213
	2050	24%	51	367	105	215
	2085	29%	65	416	80	228
		Summer rainfall				
Cressy	Baseline	38%	52	321	45	137
	2050	39%	59	396	32	152
	2085	40%	59	298	32	146
Forthside	Baseline	38%	56	331	34	146
	2050	38%	62	385	32	161
	2085	39%	60	315	26	156
Scottsdale	Baseline	34%	50	331	51	147
	2050	36%	57	305	42	159
	2085	39%	59	359	33	151

CV: coefficient of variation, Stdev: standard deviation

Table 5.7 Annual and seasonal variability in the projected multi-model 30 year meann rainfall for the baseline, 2050 and 2085 at Bomet and Kabete under the RCP8.5. Baseline period is 1961-1990.

Site	**Period**	**CV (%)**	**Stdev**	**Max**	**Min**	**mean**
		Annual rainfall				
Bomet	Baseline	23%	537	3652	1208	2353
	2050	22%	272	2022	579	1243
	2085	21%	280	2298	642	1336
Kabete	Baseline	43%	463	2587	357	1080
	2050	40%	433	2568	357	1082
	2085	32%	391	2287	489	1207
		OND rains				
Bomet	Baseline	44%	286	1538	207	650
	2050	26%	177	1239	312	668
	2085	26%	194	1455	305	748
Kabete	Baseline	67%	170	938	34	253
	2050	56%	187	960	21	332
	2085	51%	238	1053	43	464
		In-crop (SR)				
Bomet	Baseline	45%	280	1474	173	617
	2050	26%	181	1234	331	702
	2085	24%	187	1452	351	778
Kabete	Baseline	69%	237	1162	7	582
	2050	57%	253	1234	55	470
	2085	43%	243	1191	83	478
		MAM rains				
Bomet	Baseline	56%	337	1289	39	597
	2050	53%	190	1001	35	360
	2085	52%	197	821	41	380
Kabete	Baseline	80%	224	932	5	278
	2050	72%	192	775	4	266
	2085	69%	191	900	13	276
		In-crop (LR)				
Bomet	Baseline	39%	342	1755	239	874
	2050	50%	193	1048	48	388
	2085	47%	188	848	85	400
Kabete	Baseline	49%	283	1396	56	577
	2050	59%	274	1204	45	466
	2085	60%	285	1486	67	477

CV: coefficient of variation, Stdev: standard deviation, OND: October-November-December (Short rains). MAM: March-April-May (Long rains)

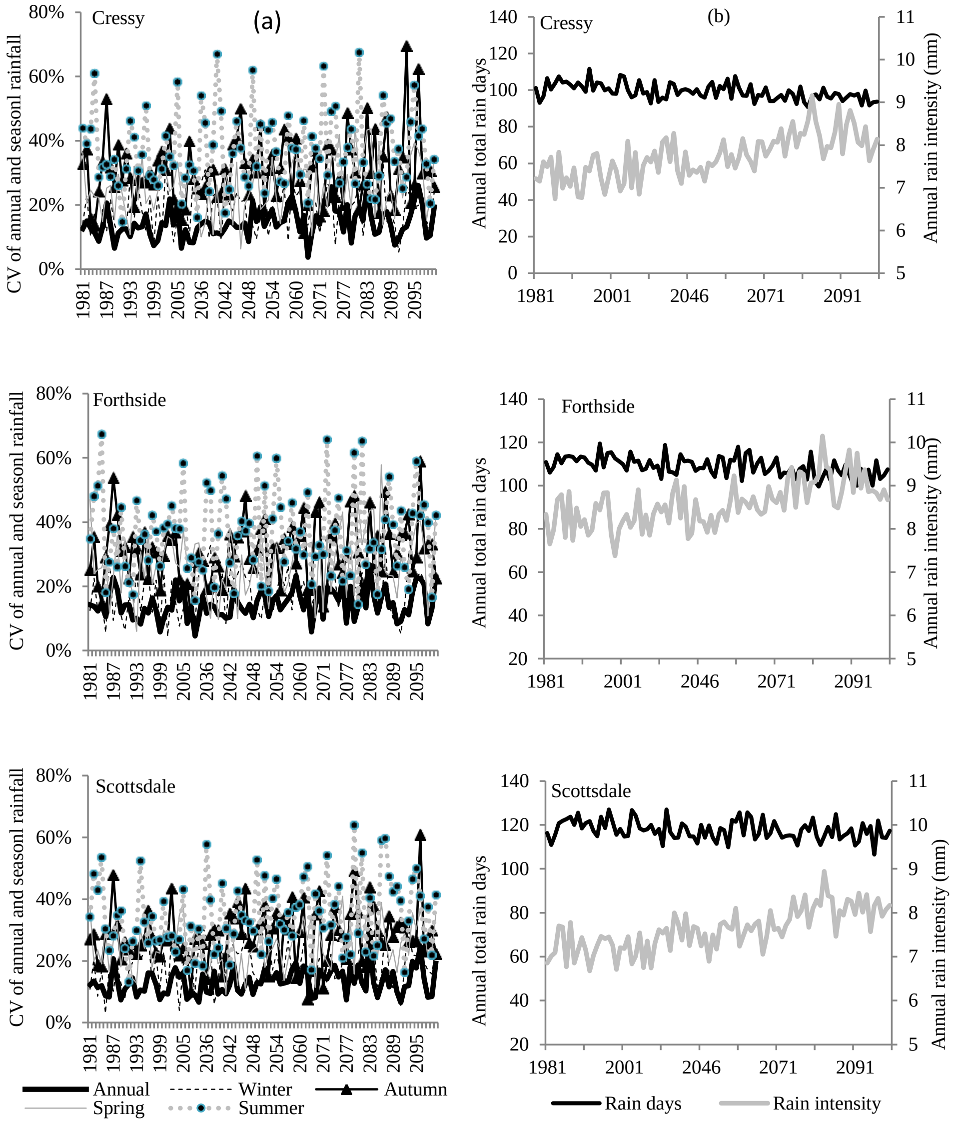

Figure 5.4 Multi-model 30-year CV (%) of annual and seasonal rainfall (a) Multi-model mean of the annual total number of rain days (>1 mm) and multi-model mean annual rainfall intensity (mm) (b) at Cressy, Forthside and Scottsdale for the baseline (1981-2010), 2050 and 2085 under the A2 emission scenario.

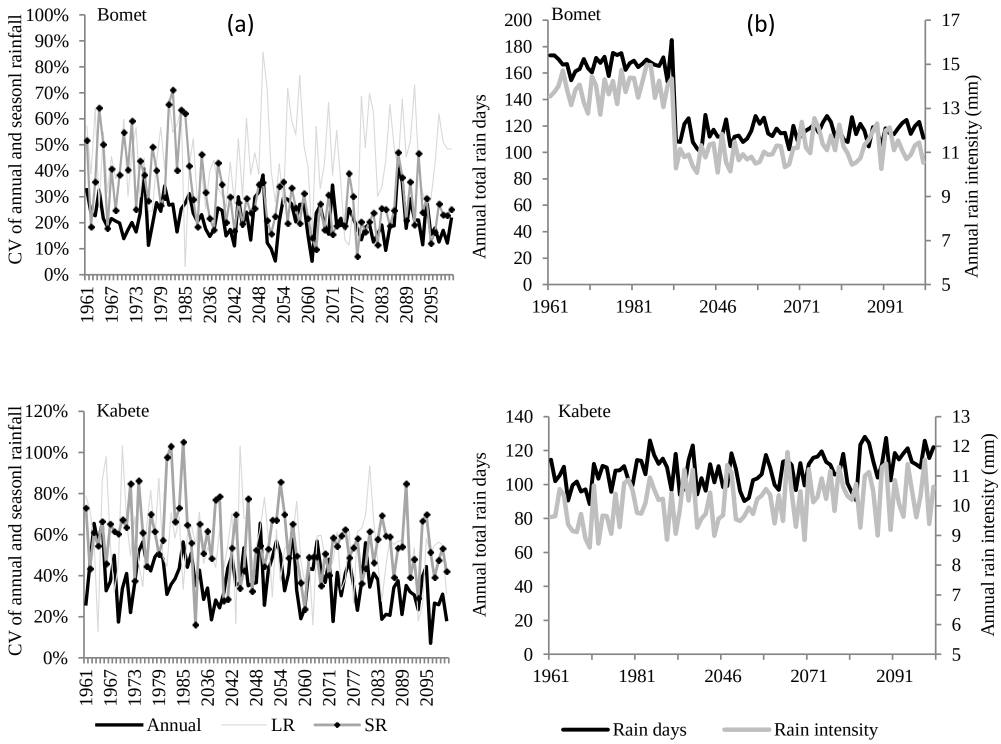

Figure 5.5 Multi-model 30-year CV (%) of annual and seasonal rainfall (a) Multi-model annual total number of rain days (>1 mm) and annual rainfall intensity (mm) (b) at Bomet and Kabete for the baseline (1961-1990), 2050 and 2085 under the RCP8.5.

Modelling

The Agricultural Production Systems simulator (APSIM-potato) model, (version 7.5), a recent development in the Plant Modelling Framework (Brown et al. 2014) as described by Brown et al. (2011) was used to assess the potential impacts of the projected climate on potato productivity at each of the five sites in Tasmania and Kenya. The model has been shown to realistically simulate in-season and end-of season tuber yield for sites within Australia (Chapter 3) and in Kenya (Chapter 4).

In Tasmania, ‘Russet Burbank’ was used, a long-day late maturing cultivar with tuber initiation and canopy development occuring over a relatively longer period (Beattie 2010). ‘Shangi’, a short-day, early maturing cultivar was used in Kenya. Soil data (physical, chemical and hydraulic properties) used to initialize the simulations are detailed in Appendix 4. Typical crop agronomical practices (Table 5.3) for a precision irrigated potato field (Tasmania) and a typical rain-fed low input system (Kenya) were iniated for the respective simulations for 90 years. We assumed that cultivar selection would remain constant (although in reality farmers will adapt to the changing climate pattern and may select an alternative cultivar). Similarly, we purposely used the same soil (physical and chemical) variables for all the simulations and initial soil water and nitrogen were reset for every simulation. At each site, planting date was fixed within the sowing window in the respective region (Table 5.3). Crop husbandry was assumed to remain constant. Thus crop management and the same soil parameters, both physical and chemical, were used for each site as the principle aim was to determine the impact of climatic differences and trends.

Additonally, atmospheric CO_2 concentrations were obtained from the Integrated Science Assessment Model (ISAM) model conversion, under the A2 scenario, atmospheric concentrations increased from the baseline (353 ppm) to 819 ppm by the end of the century (Nakicenovic & Swart 2000) while for the RCP8.5, the levls increased from 316 ppm at the start of baseline (1961 -1990) to 936 ppm by 2100 (Meinshausen et al. 2011).

Results

Impacts of projected climate change on potato growth and tuber yield

Under the A2 emission scenario, projected changes in tuber yield for ‘Russet Burbank’ across the three sites investigated in Tasmania (Table 5.8 and Fig. 5.6) was marginal. On average a 0.2% increase is projected by 2085 relative to the baseline tuber yields of 20.5 t DM ha^{-1}

(tuber dry matter yield) with minimal difference between the three sites. Similarly, the variation in tuber yield among the six GCMs was minimal (Fig. 5.6).

There is a steady increase in rate of accumulation of growing degree days (GDD) from planting to harvesting by up to 5.2% at Cressy, 4.0% at Forthside and 5.2% at Scottsdale by 2050 and by a range of 12.1 to 12.7% across the 3 sites by 2085 relative to the baseline period. The increase in the rate of accumulation of GDD is projected to shorten the time to crop maturity as the crop accumulates the required thermal time of approximately 1640 °C.d. (2 °C base) 10 days (11.9 days at Cressy, 10.4 at Forthside and 8.1 at Scottsdale) earlier than the baseline period by 2050 and 15 days (a range of 11.2 to 17.5 days) earlier by 2085 (Fig.5.7). The simulations results indicate a slight reduction in irrigation requirement by 2.1% by 2050 and 0.3% by 2085 across the three potato-growing regions (Table 5.8).

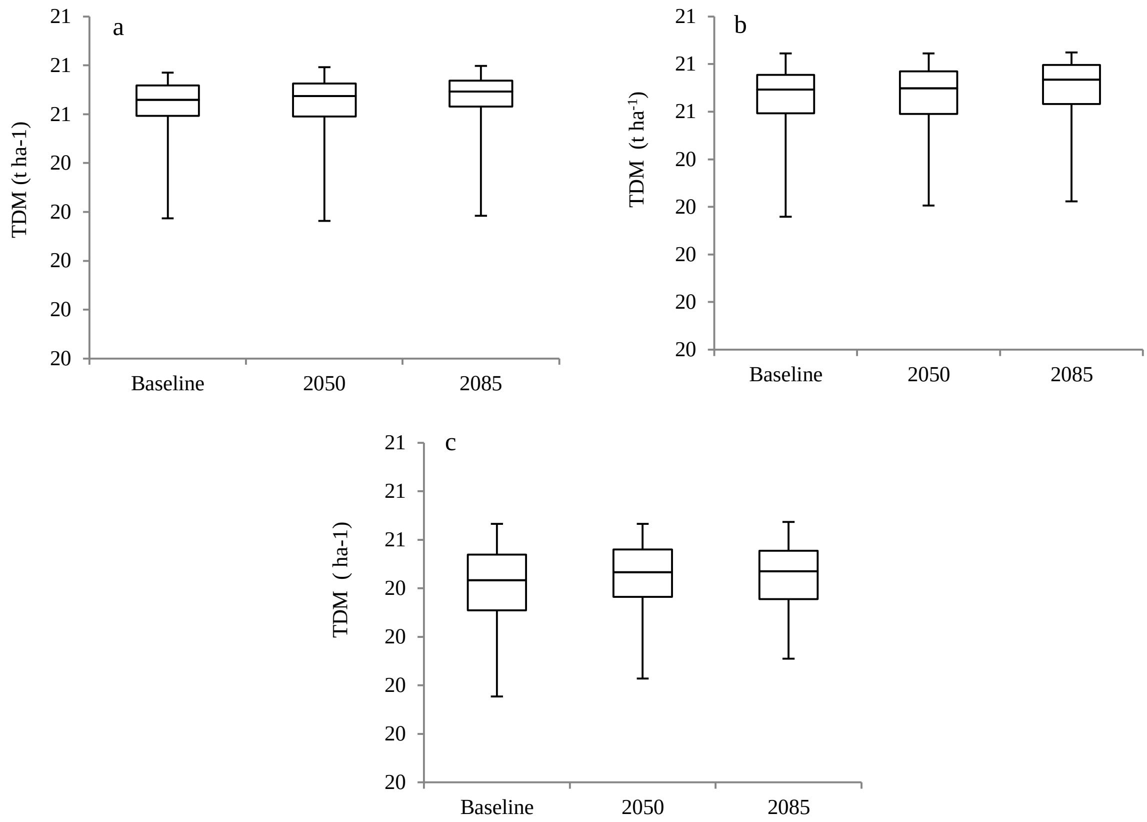

Figure 5.6 Multi-model mean tuber dry matter yield (TDM, t ha^{-1}) under A2 emission scenario at Cressy (a), Forthside (b), and Scottsdale (c). The boxplot shows the 25, 50 and 75 percentile. The whiskers show 5% and 95% percentile.

Table 5.8 Simulated changes (%) in multi-model 30 year mean annual potato tuber dry matter (TDM) yield of 'Russet Burbank' and irrigation amounts under the A2 emission scenario at Cressy, Forthside, and Scottsdale.

Site	Baseline	2050	2085	Baseline	2050	2085
	TDM			Irrigation		
	t ha^{-1}	%Δ	%Δ	mm season^{-1}	%Δ	%Δ
Cressy	20.6	0.0	0.2	498	-0.1	1.3
Forthside	20.5	0.0	0.2	376	-3.9	-2.2
Scottsdale	20.4	0.2	0.2	357	-2.4	-0.1

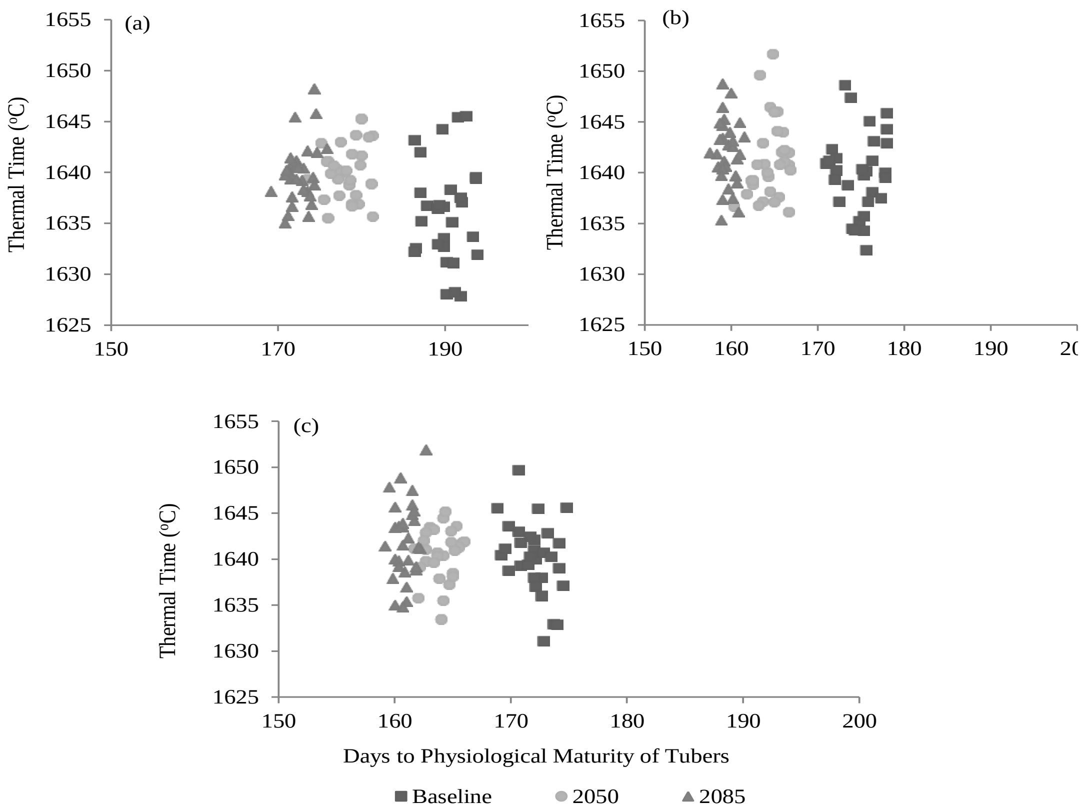

Figure 5.7. Projected multi-model 30-year mean number of days when potato plant will accumulate the required thermal time (GDD,°Cd) for physiological maturity of tubers under the A2 emission scenario at Cressy (a), Forthside (b) and Scottsdale (c).

In Kenya, simulated changes in the MME mean tuber yield for ‘Shangi’ (Table 5.9 and Fig 5.8) under RCP8.5 varied with the site and cropping season. In Bomet tuber yield is projected to increase during both cropping seasons with a 25.1% increase by 2050 during SR and by 32.5% in the LR. Similar trend are evident at Kabete by 2085, where both an increase and reduction in tuber yield is projected with a marked variability among the models used: -8.2 to 17.9% is projected during the LR by 2050 and a reduction by -0.3% by 2085. For the SR, an increase of 20.9% (model range of -5.8 to 33.6%) is projected by 2050 and by 30.7% with a model range of 16.8 to 59.5% by end of the century.

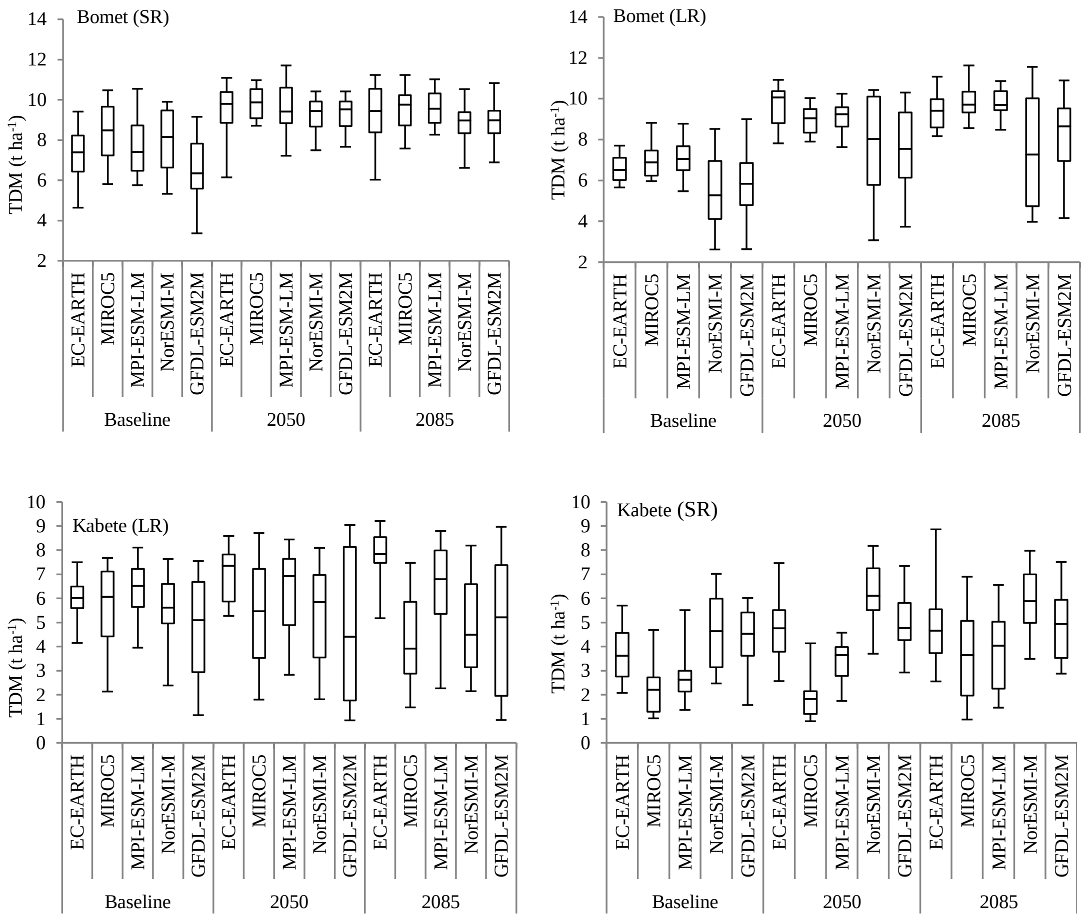

Figure 5.8 Projected mean annual tuber dry matter yield (TDM, t ha^{-1}) for baseline period (1961-1990), 2050 and 2085 under RCP8.5 at Bomet during the SR and LR and Kabete SR and LR. The boxplot shows the 25, 50 and 75 percentile. The whiskers show 5% and 95% percentile. SR: Short rains, LR: Long rains.

The simulated results for Kenya for selected years categorised into percentiles: 10th percentile classified as a poor year and 90th percentile as a good year. The simulation results shows that a poor year either Bomet or Kabete is associated with low in-crop rainfall and high leaf water (fw) and leaf expansion stress levels (Table 5.10). Unlike in Tasmania (exemplified by Cressy) where intensive irrigation is practised, the crop has ample supply of water as indicated by very low levels of fw and leaf expansion stress levels (Table 5.10). In some cases (e.g. 1984, 1988 and 2092) in Bomet, tuber yield was poor despite having received substantial amounts of in-crop rainfall. A closer analysis shows that during these years, poor rainfall distribution or inadequate rainfall received when the crop was at a critical growth stage (tuber bulking growth). This was also true for the years 2099 at Kabete (Table 5.10).

Table 5.9. Simulated changes (%) in multi-model ensemble mean of tuber dry matter (TDM) of 'Shangi' under the RCP8.5 by 2050 and 2085 during the short (SR) and long rains (LR) at Bomet and Kenya. Baseline period is 1961-1990.

Site/GCM	Baseline		2050s		2085	
	TDM (t ha^{-1})		TDM (%Δ)		TDM (%Δ)	
	SR	LR	SR	LR	SR	LR
Bomet						
EC-EARTH	7.3	6.8	29.2	41.8	27.1	39.4
MIROC5	8.4	7.0	16.6	27.4	13.1	40.5
MPI-ESM-LM	7.7	7.1	24.2	27.7	24.0	37.7
NorESMI-M	7.9	5.8	16.6	29.6	11.6	31.6
GFDL-ESM2M	6.5	5.7	43.1	36.4	37.3	41.7
MME	7.5	6.5	25.1	32.5	21.9	38.3
Kabete						
EC-EARTH	3.7	5.8	28.3	17.9	32.9	29.4
MIROC5	2.3	5.4	-5.8	-5.2	59.5	-23.3
MPI-ESM-LM	3.0	6.2	15.1	-0.6	31.1	3.9
NorESMI-M	4.6	5.3	33.6	-8.2	27.3	-19.1
GFDL-ESM2M	4.2	4.4	19.1	3.2	16.8	5.7
MME	3.6	5.4	20.9	1.6	30.7	-0.3

MME: Multi-Model Ensemble mean

Overall, the simulated tuber yield shows less variability in Bomet compared to Kabete. In Bomet tuber yield during the SR are less variable than in the LR while the opposite is true at Kabete with LR tuber yield depicting less variability compared SR.

Examination at the annual and seasonal daily maximum (Tmax) temperatures shows an increase in the number of days when daily Tmax is within the high temperature (Ht) range: ≥ 24 ^{o}C <34 ^{o}C is projected at all the five sites (i.e the 3 sites in Tasmania and 2 in Kenya) by 2085 from the baseline (Fig. 5.9a and Fig.5.10). In Tasmania, the highest increase in annual number of Ht days is projected at Forthside where 60 Ht days are projected by 2085 from 15 days at baseline compared to 89 days up from 42 days at Cressy and 84 days at Scottsdale up from 29 days at baseline. Increase in the number of Ht days is also projected for summer and spring (Fig.5.9a). At all the three sites there are no days when daily Tmax is within the very high temperature (VHt) range: >34 ^{o}C.

The number of days when daily minimum (Tmin) is <2 ^{o}C (frost days) are projected to decrease at all the three sites in Tasmania by 2085 from the baseline (Fig. 5.9b). The highest reduction in annual number of frozen days is projected at Forthside , 91% reduction by 2085 compared to 50% reduction at Cressy and 67% reduction at Scottsdale relative to the number of frozen days at baseline. Reduction in the number of frozen days is also projected for summer and spring (Fig.5.9b).

Table 5.10 The level of stress factors exerted on potato plant: leaf expansion stress factor (leafFexp.), leaf nitrogen stress factor (leafFn), leaf water stress factor (leafFw) and transpiration efficiency based on carbon dioxide levels (Fco_2) for a poor (10th Percentile) and a good (90th Percentile) year. Stress values for Tasmania crop are exemplified by Cressy.

	GCM	Year	TDM	LeafExp	LeafFn	Leaf Fw	Fco_2	Incrop rainfall (mm)	Tmean (oC)
10th Percentile									
Bomet SR									
Baseline	GFDL-ESM2M	1988	5.6	0.4	0.9	0.5	1.0	351	17.4
2050	GFDL-ESM2M	2037	7.9	0.6	0.9	0.8	1.1	504	17.6
2085	GFDL-ESM2M	2092	7.5	0.8	0.9	0.9	1.2	858	17.9
Bomet LR									
Baseline	NorESMI-M	1984	3.3	0.4	0.9	0.5	1.0	452	18.9
2050	GFDL-ESM2M	2047	4.1	0.6	1.0	0.7	1.1	281	17.9
2085	NorESMI-M	2086	3.5	0.3	0.9	0.5	1.2	143	20.7
Kabete SR									
Baseline	MPI-ESM-LM	1975	0.8	0.2	0.9	0.3	1.0	76	22.0
2050	MPI-ESM-LM	2039	1.3	0.2	0.9	0.3	1.1	139	24.4
2085	MPI-ESM-LM	2099	1.9	0.4	0.9	0.5	1.3	451	27.0
Kabete LR									
Baseline	GFDL-ESM2M	1988	2.7	0.5	0.7	0.6	1.0	353	22.1
2050	GFDL-ESM2M	2044	1.4	0.5	0.8	0.7	1.1	315	24.5
2085	MIROC5	2099	1.6	0.5	0.8	0.6	1.3	228	27.2
90th Percentile									
Bomet SR									
Baseline	MIROC5	1979	9.8	0.6	0.9	0.8	1.0	691	16.2
2050	EC-EARTH	2061	10.8	0.7	0.9	0.8	1.2	612	17.1
2085	MPI-ESM-LM	2079	10.9	0.7	0.9	0.8	1.2	671	19.8
Bomet LR									
Baseline	MPI-ESM-LM	1980	6.8	0.7	1.0	0.8	1.0	561	17.5
2050	EC-EARTH	2064	10.1	0.8	0.9	0.9	1.2	402	17.8
2085	MPI-ESM-LM	2097	10.8	0.9	0.9	1.0	1.3	622	20.9
Kabete SR									
Baseline	MPI-ESM-LM	1969	5.6	0.3	0.9	0.5	1.0	278	20.9
2050	NOAA	2051	6.9	0.7	0.9	0.8	1.1	693	21.0
2085	MIROC	2088	7.0	0.4	0.9	0.6	1.3	446	25.1
Kabete LR									
Baseline	ICHEC	1988	7.3	0.8	0.9	0.9	1.0	856	20.1
2050	NOAA	2038	8.2	0.5	0.9	0.7	1.1	360	22.6
2085	MPI-ESM-LM	2090	8.5	0.6	0.9	0.8	1.3	786	25.6
10th Percentile									
Tasmania	Cressy								
Baseline	GFDL2	1987	20.2	1.0	0.9	1.0	1.0	413	14.7

2050	GFDL2-1	2045	20.2	1.0	0.9	1.0	1.1	205	16.7
2085	CSIRO	2074	20.3	1.0	0.9	1.0	1.2	315	17.8
90th Percentile									
Tasmania	Cressy								
Baseline	CSIRO	1985	20.8	1.0	0.9	1.0	1.0	354	14.5
2050	ECHAM	2060	20.8	1.0	0.9	1.0	1.1	424	16.6
2085	MIROC	2089	20.8	1.0	0.9	1.0	1.2	509	18.3

A value of 1.0 of leafFw, leafExp and leafFn indicates no water stress and the lower the value the more water stress, SR: short rains, LR: long rains

In Kenya, the highest increase in annual number of Ht days is projected at Bomet where 205 Ht days are projected by 2085 from 90 days at baseline. However, the total number of days is much higher at Kabete (Fig.5.10). Increase in the number of Ht days is also projected for LR and SR at both sites (Fig.5.10). There are no days in Bomet when Tmax is projected to be within the very high temperatures (VHt) range: >34 ^{o}C but an increase in the number of VHt days is projected at Kabete: 33 days by 2085 from 0 (zero) day at baseline.

Additional analysis on the effect of increasing atmospheric CO_2 exemplified by the data for Kabete (SR and LR) shows that simulated tuber yield were progressively enhanced by elevated CO_2 . This was done by running simulation with two levels of atmospheric CO_2 concentrations (ambient concentration of 380 ppm and increasing levels as per RCP 8.5 levels (Fig.5.11). The data showed that tuber yield increased by 32% (SR) and 48% (LR) with a doubling of atmospheric CO_2 concentration (380 ppm compared to a mean value of 807 ppm under RCP8.5) by 2085 relative to the baseline period of 1961-1990.

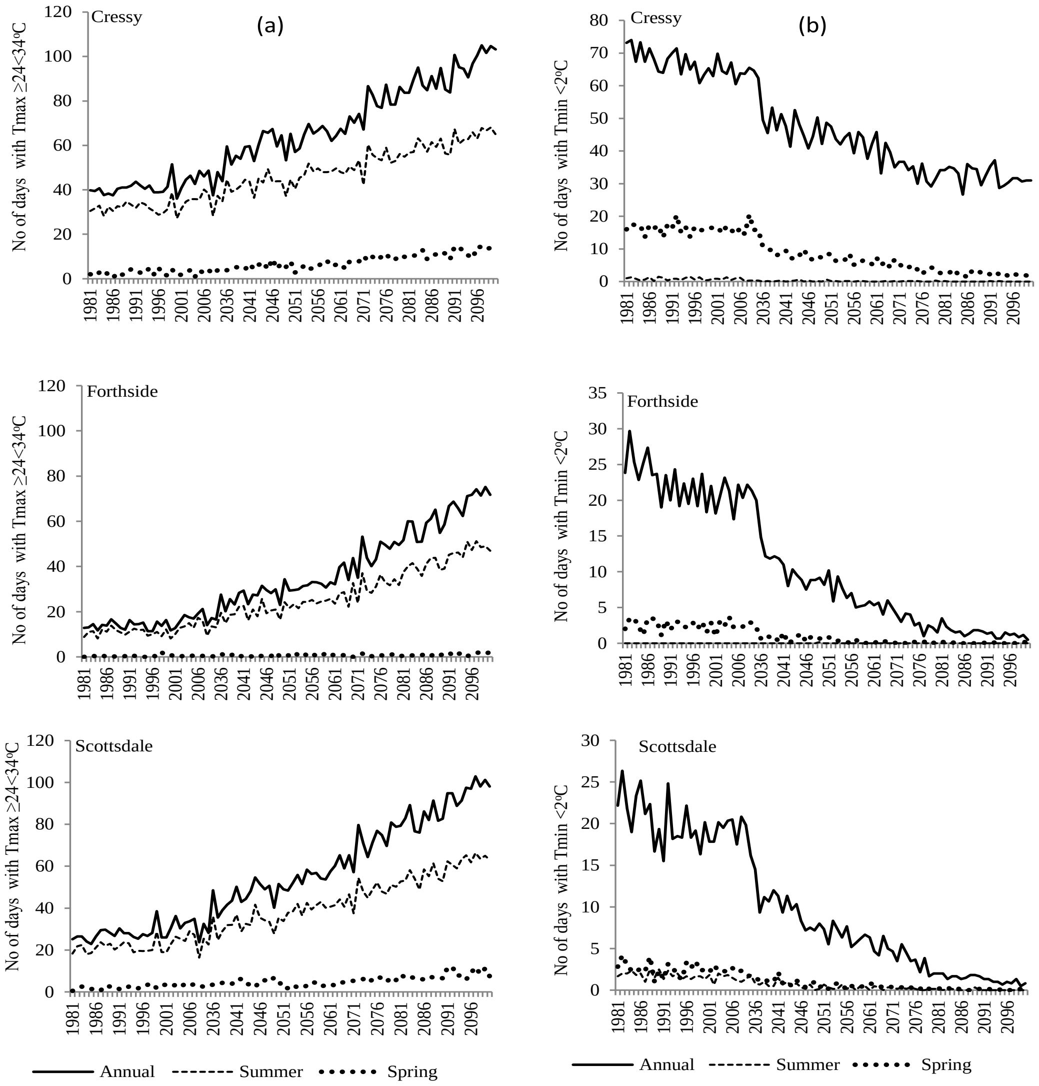

Figure 5.9 Multi-model mean of total annual and seasonal number of days with Tmax ≥24 ^{o}C but <34 ^{o}C (a) Multi-model mean of the total annual and seasonal (spring and summer) number of days with Tmin <2 ^{o}C (b) at Cressy, Forthside and Scottsdale for the baseline (1981-2010), 2050s and 2085 under the A2 scenario. Potatoes are planted in mid-spring and early summer and harvested early autumn.

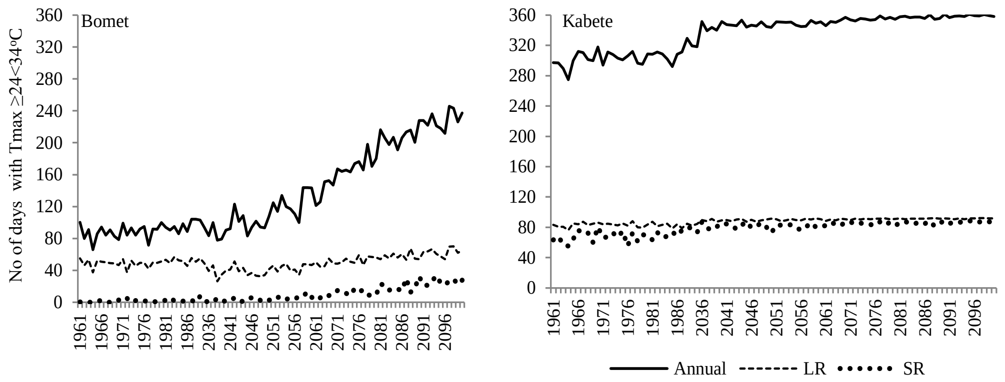

Figure 5.10 Multi-model mean of total annual and seasonal (LR and, SR) number of days with Tmax ≥24 °C but <34 °C at Bomet and Kabete for the baseline (1961-1990), 2050s and 2085 under the RCP8.5. Potatoes are planted twice in a year; during the March-April-May (MAM) or “Long Rains” (LR), and October-November-December (OND) “Short Rains” (SR) at both two sites.

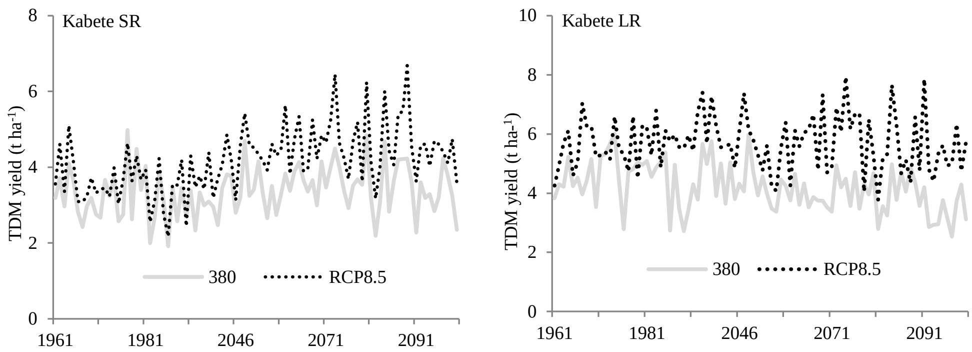

Figure 5.11 Effects of CO_2 fertilization on multi-model mean tuber dry matter (TDM, t ha^{-1}) yield of ‘Shangi’.The values shown are mean TDM for 1961-1990, 2036-2065, 2071-2100 on a continuous basis. The effect was estimated by comparing projected TDM under ambient CO_2 concentration of 380 ppm and increasing levels as per RCP 8.5 levels at Kabete during short rains (SR) and long rains (LR)

Discussion

Many climate change studies have used potato yield as a parameter to indicate the impact of a warmer climate on this crop (Hijmans 2003; Holden & Brereton 2006; Saue & Kadaja 2011; Kumar et al. 2015). Impacts on crop yield depends on the location, choice of and the level of adaptation (Hijmans 2003; Holden & Brereton 2006; Ebi et al. 2011; Supit et al. 2012; Kumari et al. 2015; Pulatov et al. 2015; Resop et al. 2016)). Beside tuber yield, other indices used to denote the negative or positive impacts of climate change on potato production are growing day degrees, heat days, frost/chill days and the length of the growing season (Hijmans 2003; Molahlehi et al. 2013; Pulatov et al. 2015). Although temperatures are projected to increase in the Tasmanian potato growing regions, potatoes are rarely exposed to temperatures outside its optimum range for growth e.g. the number of days when daily mean temperatures are within the high temperature range (≥ 24 °C but <34 °C) increases from less than 1 day during the baseline period to 2, 5 and 7 days at Forthside, Cressy and Scottsdale respectively by 2085. Increase in mean temperatures and reduction in the number of frost days projected for summer and spring may mean that potato growers in Tasmania can plant their potatoes earlier in future, although the risk of sporadic and damaging frosts may remain significant.

The duration to crop maturity is projected to be shortened by 10-15 days in line with the gradual increase in rate of accumulation of GDD, by up to 4.8% by 2050 and 12.3% by 2085 relative to the baseline period. Elevated CO_2 has been shown to contribute to shortening of crop duration due to accelerating time to flowering and leaf senescence (Miglietta et al. 1998). Shortening of the duration to tuber maturity did not affect the projected tuber yield of 'Russet Burbank'. This might be explained by the long growing season in Tasmania, up to 200 days (Beattie 2010) and the relatively small projected shortening of crop duration to maturity. The simulated crop also had ample water supply as irrigation was triggered when 35% of available soil water content (ASW) was depleted and irrigation water was applied down to a soil depth of 400 mm as well as optimum nitrogen fertilization.

The reduction in crop growing duration has been reported for other crops in Tasmania. For example, time to maturity for the current varieties of grapes in Tasmania are projected to shorten by more than two months by the end of the century (Holz et al. 2010). A study by Pulatov et al. (2015) indicates that a warmer climate in northern Europe will reduce the impact of Colorado potato beetle pest and late blight because early planting and harvesting allows the crop to escape damage. However pests and diseases do not currently pose significant threats to potato production in Tasmania compared to other regions and are well managed. Thus it is difficult to predict what a shortening of 10 - 15 days will imply for potato production in Tasmania. This situation could change as shifts in climate encourage the establishment of pests and diseases or if strict biosecurity regulations are not maintained (Boland et al. 2004; Hannukkala et al. 2007; Luck et al. 2011; Kroschel et al. 2013).

In Kenya, inter-annual variability in projected crop yield and the large disagreements among GCMs in predicting rainfall may be reflective of a large magnitude of future warming relative to historical variability in the tropics (Lobell & Burke 2008). Simulation results for tuber yield showed a similar pattern to rainfall across the study sites and time horizon in Kenya with maximum tuber yield corresponding to years with high rainfall. Poor rainfall distribution within a year had a strong effect with cases where low yields were obtained even in years with high in-crop rainfall (>500 mm). The results corroborates with findings by Lobell and Burke (2008) to the effect that rainfall amount and distribution plays a critical role in year-to-year variability of crop yields under rain-fed conditions.

APSIM simulates crop water stress using the ratio of soil water supply to potential water demand with a value of 1.0 indicating no water stress and lower values indicating more water stress (Lobell et al. 2015). Simulation results shows that water shortages occurs both in

Bomet and Kabete but are more pronounced and more frequent in Kabete with values of water stress factor ranging from 0.3 to 0.7 (poor year) and 0.5 to 0.9 (good year) compared to 0.5 to 0.9 (poor year) and 0.8 to 1.0 (good year) in Bomet. Thus a crop grown in Kabete is exposed to high level of water stress and for longer period than a crop grown in Bomet. This explains the simulated lower yields in Kabete compared to Bomet. This is contrast to the irrigated crops in Tasmania where the crop is exposed to minimal water stress with simulated water stress values of 1(one) throughout the growing season.

As temperature and atmospheric CO_2 increases, the interaction between these factors and rainfall determined the growth and development and end-of-season tuber yield. In Bomet, the projected temperature increase is less than in Kabete and even with the increase, the future temperature is still within the ideal range for optimum crop growth. Also, the positive effect of increasing atmospheric CO_2 may have compensated for the negative effect of increasing temperatures particularly in Kabete. This contributed to the projected positive impact of a projected warmer climate on tuber yields in Bomet and Kabete.

These findings agrees with those by Lizana et al. (2017) in which thermal treatment through increase in temperature by 2.3 to 5.3 °C did not have a detrimental effect on tuber yield as long as the mean temperature was still within the optimum range. According to these authors, tuber yield increased by 11-59% depending on the cultivar and the growth stage at which thermal treatment was introduced. Reliant on nutritional and water limitations, potato tuber yield increases under elevated CO_2, (Kumari and Agrawal, 2014; Kumari et al., 2015; Miglietta et al., 1998). In contrast, these results disagree with many other previous studies which showed a detrimental effect of a warmer climate on potato productivity (Hijmans 2003; Resop et al. 2016; Fleisher et al. 2017; Zhou et al. 2017).

Some of the previous climate impact studies on potato (Rosenzweig et al. 1996; Hijmans 2003) did not fully considered the effect of rising atmospheric CO_2 concentration rather these studies focused on effect of elevated temperatures. In the present study, rising CO_2 concentration was considered based on ISAM values. Because of the increase in CO_2 concentrations, transpiration efficiency increased linearly over time from a value of 1 during the baseline period to a maximum value of 1.37 at the end of the century. Coupled with other benefits of elevated CO_2 including enhanced radiation use efficiency (Reyenga et al. 1999; Lobell et al. 2015), increased net photosynthetic rate and reduction in stomatal conductance (Kaminski et al. 2014) and improved nitrogen efficiency (Ghahramani et al. 2015) contributed partly to the projected positive impacts of tuber yields in a warmer climate in Kenya. Importantly, positive impacts may be because temperatures during the simulated growing period were not excessively high as to impact carbon allocation to tubers and/or to impact leaf expansion rates.

According to (Kaminski et al. 2014), tuber yield of potato plants grown under 1000 ppm increased by up to six-fold relative to plants grown under 380 ppm with variances among the cultivars. However, there are uncertainties associated with these results in particular for projections for 2050 and beyond when CO_2 levels are above 500 ppm. There are several sources of variation and uncertainties in projected impacts of climate change on agriculture including emission scenario, type of model used, management levels, soil and climatic conditions (Murphy et al. 2004; Olesen et al. 2007). To reduce the variation in projected impacts, Fleisher et al. (2017) recommends the use of multiple models to simulate impacts and incorporation of adaptation options. Simulation results presented in this study are pure impacts without any adaptations to the changes in climate and only one model was used.

Projected reduction in irrigation amount in Tasmania can be explained by enhanced water use efficiency and reduction in stomatal conductance. The reduction in irrigation water requirement is in agreement with findings by Ghahramani et al. (2015) to the effect that by 2030, there will be a greater opportunity to increase overall water use efficiency of Australian wheat belt due to CO_2 fertilization. The findings are however; in contrast with other studies that showed that net irrigation requirements would, increase in future because of global warming which in turn increases evapotranspiration and reduces relative humidity thereby increasing vapour-pressure deficit (VPD). According to data from Zhao et al. (2015), projected climate change increased the net irrigation requirements (NIR) of six major crops including potatoes in the Mediterranean region of Europe by a sizeable margin of up to 182 mm yr^{-1}.

In Tasmania, simulation results indicate that tuber yield will remain unchanged throughout the century. However, shortening of duration to maturity could potentially translate to savings in amount of irrigation as well as reduction in amount of pesticides used. Simulation results indicate a slight reduction in irrigation amounts of 3.1% by 2050 and 1.3% by 2085 across the three potato growing region. These modelling results highlight the potential competitive advantages of Tasmanian potato industry as climate changes but do not include other significant information, which might influence potato production. In the important NW potato growing region of Tasmania represented by Forthside, towards the end of the century rainfall is expected to increase up to 20% in winter and spring and decrease by 10-20% during summer and autumn (Corney et al. 2010). These changes in rainfall are expected to generate more intense downpours along with longer dry periods. While irrigation may be applied in dry periods the management of waterlogging in potatoes is more problematic (Levy & Coleman 2014; Pavek 2014). This increase in rainfall intensity is also likely to increase the risk of soil erosion.

In Kenya, simulation results indicate the need for irrigation as a way of optimising as well as stabilizing tuber yield. Based on data from Kadaja and Saue (2016), irrigation can increase tuber yield by 18 to 26% and significantly reduce variability. Introduction of supplementary irrigation at the most sensitive growth stages may be the most appropriate option for stabilizing and optimising production in Kenya. This is necessary as the simulated results revealed intermittent short to medium periods of water stress. Notably, the yields currently obtained by farmers in Kenya are way below the potential yields and thus the need to close the yield gap.

Given that the potato has higher water use efficiency compared to major food crops (maize, wheat and rice), (Birch et al. 2012) introducing irrigation will to improve production of the potato in areas where temperature is within the optimum range. Moreover, there is a possibility of benefiting from enhanced water use efficiency due to elevated atmospheric CO_2 especially under rain-fed conditions.

Also important in Kenya in particular for Kabete is the need to introduce thermo-tolerant cultivars. Compared to others cultivars, thermos-tolerant cultivars have higher tuber yield under heat and water stress conditions. For example in China, *Solanum tubersosum*, 'Jizhangshu 8', a CIP-bred clone (CIP Accession No.390478.9, known as Tacna in Peru), with drought, heat, and salinity resistance has been widely adopted in drought prone areas of the country since it was registered in 2006 (Carli et al. 2014).

For studying impacts of climate change, it is important that projected climate data used for simulations are 'bias-adjusted'. This procedure ensures that errors that typically occur in projected climate data are corrected. Projected climate data from Climate Future Tasmania that was used in the study is bias-adjusted and as such there was good agreement between the six models used in the study. This was not the case in Kenya where the projected climate data obtained from ICPAC was not bias-corrected. Consequently there was poor agreement between the five models used in Kenya and this and have contributed to large variability in the simulated tuber yield.

Conclusion

In Tasmania, simulation results indicate that tuber yields will remain unchanged throughout the century. However, there is a steady increase throughout the century in rate of accumulation of GDD and hence earlier harvesting. Shortening of duration to maturity could potentially translate to savings in amounts of irrigation as well as reduction in amounts of pesticides used. The projected tuber yield of 'Shangi' in Kenya varied with location and cropping season but overall, an increase is projected for the two study sites.

Our results illustrate that as temperature and atmospheric CO_2 increases, the interaction between these factors and rainfall determines tuber yield in rain-fed conditions. If the temperatures are within the optimum range or potato plants are exposed to short term period of high temperatures, tuber yield are driven by rainfall amount and distribution. Poor distribution had a stronger effect with cases where low yields obtained even in years with high rainfall.

Due to marked inter-annual and inter-seasonal variability in rainfall in Kenya, there is need to prioritise development of irrigation systems to optimise and stabilise tuber yield. Since potato plays an important role as a food and nutritional security crop, further research on impacts of climate change on quality of tubers and on pest and disease incidence are recommended. Intensive studies on adaptation of pest resistance and thermo-tolerant cultivars are also needed. In terms of generating future climatic data, refinement of the projected data and bias-adjustment is recommended for Kenya as there were large disagreements among the projected datasets generated by the GCMs used in the study to generate future climate data for study sites in Kenya.

Acknowledgements

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Chapter 6 : General Discussion and Conclusion

Overview

The application of APSIM crop modelling in simulating potato productivity to facilitate the assessment of climate change impact on potato growth was the goal of this dissertation. The impact of climate change on the potato productivity has never been researched either in Tasmania (Australia) or in Kenya. The three experimental investigations presented in Chapters 3-5 are complementary though independently each investigation addresses a specific objective that contributes to the overall goal.

Previous to this doctoral study, APSIM-potato had only been tested and calibrated with a number of datasets from a long-term experiment conducted in Lincoln, New Zealand where for the cultivar 'Russet Burbank' it accurately reproduced the potatoes response to different rates of N-fertilizer, sowing dates, plant density, and irrigation treatments. Further parameterisation and evaluation was carried using field data from different locations and cultivars in both Tasmania and Kenya. In Tasmania, model performance was tested under optimal irrigated management but in Kenya performance was tested under suboptimal heat and water stress. It was concluded that tuber yield for the Tasmanian (Chapter 3) and Kenyan (Chapter 4) cultivars was simulated with a degree of accuracy that justified the use of the parameterised model in climate change impact studies for potato under the Tasmanian and Kenyan potato growing conditions (Chapter 5).

This final chapter of my thesis highlights the role of potatoes in ensuring global food security and links this role to the need to have good tuber prediction under various management options both now and in a future changed climate. Ways in which that the potato industry can adapt to climate change, minimising any negative impact and taking advantage of opportunities are discussed. The gaps that need to be addressed by modellers to improve predictability using APSIM-potato model are identified. Lastly, the chapter concludes with recommendations for future research topics based on the outputs of this thesis.

Why develop crop modelling capacity for potato?

Global food requirements are projected to increase 50% by 2030 and 70% by 2050 (Dwivedi et al. 2013; FAO 2013). Potato (Solanum spp.) is the third most important food crop in the world after rice and wheat in terms of human consumption (Bradshaw & Bonierbale 2010; Birch et al. 2012; FAO 2015). It has been highly recommended by the Food and Agriculture Organization of the United Nations (FAO) as a food security crop as the world faces a growing population and subsequent problems with food supply (Devaux et al. 2014). Potatoes are grown in over 140 countries (FAO, 2015), more than a billion people eat potatoes and total global potato production exceeds 374 million metric tons per year (Devaux et al. 2014). Potatoes are not only a major source of carbohydrates, but also an excellent source of high quality protein, vitamins, minerals, dietary fibre and antioxidants (Bradshaw & Bonierbale 2010; Wegener et al. 2015).

The demand for potatoes in Australia has been on the decline (AUSVEG 2012) but an anticipated increase in demand for food in Asia is expected to create colossal export opportunities for Australia as it is a major supplier of agricultural commodities to Asian market (Qureshi et al. 2013). Potatoes dominate the vegetable industry across Australia (ABS 2014) and because of geographical diversity across the different States in Australia all year round production is possible (AUSVEG 2012).

Devaux et al. (2014) and Lizana et al. (2017) argues that for developing countries potato-based systems present increasingly important opportunities for the rural poor, in terms of food security, poverty alleviation, and improved health status. In Kenya, potato is considered as a strategic food commodity providing livelihoods to approximately 800,000 growers and as a staple food to millions of rural and urban consumers (Kaguongo et al., 2013). Urbanization, change of food preference and rapid population growth in Kenya will continue to create demand for potatoes (Kaguongo et al. 2013).

Climate change affects all dimensions of food security and nutrition (Wheeler & von Braun 2013). Changes in climatic conditions have already influenced the production of some staple crops, and future climate change threatens to exacerbate this (Van Oort et al. 2012; IPCC 2014a; Niang et al. 2014). Lower agricultural output means lower incomes, especially for the most vulnerable. Nutrition is likely to be affected by climate change through related impacts on food security and dietary diversity (Wheeler & von Braun 2013). Despite its expected significant role in ensuring global food security, climate change impact studies with potato are limited especially when compared to other staple crops e.g. maize, rice and wheat (Brown et al. 2011; White et al. 2011).

The application of models to simulate growth (Supit et al. 2012; Thornton & Herrero 2015) is a fast and relatively inexpensive way to enhance empirical research and provide information for a wide range of different stakeholders about the need to adapt new technologies and practices especially adaptation under climate change (Carberry et al. 2002; Oteng-Darko et al. 2013; Angulo et al. 2013.). The application of crop simulation models to potato however has not attracted much interest relative to other major crops such as wheat, rice and maize (White et al. 2011). Difficulties in computing the growth and development of underground storage organs may to some extent explain the dearth of modelling studies with potatoes (Brown et al. 2011). According to Fleisher et al. (2017) there is also difficulty in modelling potato plants due to large variation in the ploidy, its indeterminate growth pattern and lack of discrete developmental stages as compared to other crops. Although there are many potato models, most of these models have not been comprehensively tested with actual field data and thus are not capable of simulating new conditions, such as the effect of climate change (Raymundo et al. 2014; Fleisher et al. 2017)

In Australia the Agricultural Production Systems sIMulator, APSIM–potato model is not as advanced as APSIM-wheat, APSIM-maize, and APSIM-sorghum. For example, as at October 1, 2016, a search of the Web of Science journal abstract database gave 742 hits for APSIM but there only 3 APSIM publications on modelling of potato growth and development, this relating to work in Tasmania and New Zealand (Brown et al. 2011; Lisson & Cotching 2011; Sharp et al. 2011). A first step to achieving the research goal was therefore to parameterise and evaluate The Agricultural Production System Simulator (APSIM-potato) model. The publications that will follow this thesis will make a significant addition to the quantity of literature available on the use of APSIM for potatoes.

How well did APSIM potato simulate potato growth and productivity under current growing conditions?

Chapter 3 explored the precision of APSIM-potato in reproducing observed in-season and end-of-season tuber dry matter yield (TDM), aboveground biomass, LAI, phenology and N-uptake of Tasmanian potato cultivars. Chapter 4 investigated the application of APSIM-potato in tropical highland conditions in Kenya, assessing model efficiency in simulating potato growth parameters, phenology, and TDM.

One aspect that sets the APSIM modelling framework apart from other agricultural models is its ability to allow users to describe management interventions via scripting language (Holzworth et al. 2014). APSIM-potato integrates with the APSIM soil, SOILN, management, and user interface components to provide robust and user friendly simulations. As such it was possible to simulate growth and development of five potato cultivars each with distinct growth traits and phenology and grown under contrasting environment and management options. Two Tasmanian commercial cultivars ('Russet Burbank' and 'Moonlight') grown for processing were used in field experimentation and modelling simulations. Three Kenyan potato genotypes were used; two thermo-tolerant virus resistance advanced clones ('Unica' and CIP 300046.22) and 'Shangi', a farmer-selected cultivar. 'Unica' and 'Shangi' were officially registered in Kenya in 2015 and 2016 respectively.

APSIM-potato realistically predicted the observed Tuber Dry Matter (TDM) and N-uptake as well as the key phenological stages (date of emergence, vegetative and tuber initiation) for 'Russet Burbank' and 'Moonlight'. The simulations for 'Russet Burbank', particularly for TDM and tuber N-uptake in this study and those carried out previously in

New Zealand (Brown et al. 2011) demonstrate that APSIM-potato model has an excellent ability to reproduce observed TDM yield. The model was parameterised for the first time for the cultivar ‘Moonlight’ and simulation results showed that the APSIM-potato can realistically simulate the observed tuber yield and N-uptake for other potato cultivars apart from ‘Russet Burbank’ with which the module was developed.

Simulations carried out also increase confidence in the model’s ability to explore management options such as changes in inputs (water, nitrogen and fertilizer). As any new data on growth, parameters and yield for ‘Russet Burbank’ and ‘Moonlight’ become available under Tasmanian or similar conditions, the simulations in this thesis can then be improved, particularly in relation to simulation of other plant organs besides the tuber (e.g. above ground biomass, LAI). The main strength of using APSIM-potato is that it can easily be updated by overriding the current parameters once better data is made available. The dataset used in this study was only for one cropping season. More detailed descriptions of cultivar growth and development across several cropping seasons will be of great value for refining the phenological description of the crop used by the model.

Although APSIM-potato model was developed for a temperate climate and parameterised with a long day cultivar, it reasonably simulated short day cultivar phenology and ontogeny and realistically reproduced observed TDM under suboptimal tropical highland conditions in Kenya (Chapter 4). Prediction of TDM and phenology under Kenyan potato conditions was equally good as that reported in Chapter 3. Given that this was the first time that APSIM-potato was tested under tropical highland conditions, the results presented in Chapter 4 provide a foundation for further testing of the model. Refinement of the model will require collection of more long-term field crop data to improve the model's ability to simulate other plant organs such as aboveground biomass, N-uptake and LAI.

'Russet Burbank', a member of the tuberosum subspecies is a late maturing cultivar in which tuber initiation and canopy development takes place over a relatively longer period of time. Growth cycles for cultivars 'Shangi' and 'Unica' and CIP 300046.22 are relatively shorter, with intermediate tuber bulking initiation and fast-bulking rates (Condori et al. 2010). Early potato cultivars such as 'Shangi' and 'Unica' allocate a larger part of the available assimilates to the tubers early in the growing season, leading to shorter growing periods and lower yields (Kooman & Rabbinge 1996) compared with late cultivars.

The difference in earliness and bulking rate can affect model performance. For example under dry conditions, the 'Johnson' potato model under-estimated the bulking rate of both the early maturing rapid tuber bulking 'Norland' and the late maturing 'Russet Burbank'. This under-estimation was more pronounced in 'Norland' (Nemecek 1996). Also, APSIM-potato was not capable of modelling pest and diseases and other soil limiting nutrients. Due to hot dry conditions (especially during SR2013) it is possible that potato plants were affected by aphids and PTM, the effects of which could not be modelled in APSIM.

Why APSIM-potato for modelling the impact of climate change on potato production?

Some of the climate impact studies on potato including studies by Hijmans (2003) and by Rosenzweig et al. (1996) only considered the effect of temperatures and not the effect of increasing atmospheric CO_2 concentration. Raymundo et al. (2014) suggest that there will be a trade-off in certain regions as the century progresses between the positive impact of elevated CO_2 concentrations and the negative impact of increased temperatures. Thus selection of appropriate climate smart cultivars and management options for potato in the face of climate change requires an assessment of the impact of the complex interactions between changing temperature, rainfall and atmospheric CO_2 concentration.

The APSIM modelling framework has addressed many of the limitations of other models in climate change impact studies (Holzworth et al. 2014). It has been used successfully to investigate the impacts of climate change on agriculture, as well as adaptation and mitigation strategies, to assess effects of changes in atmospheric CO_2 concentration, temperature and rainfall pattern on different scenarios and to address quality components of produce, e.g. protein content of wheat grains (Holzworth et al. 2014). The APSIM-potato as described in this thesis had similar potential to explore a wide range of changing climate variables, their interactions and the impact of different management regimes on potato growth, tuber yield and quality.

Insights into the impact and significance of climate change on potato production in Tasmania and Kenya

Climate change projections in Chapter 5 suggest that for the potato growing sites in Tasmania, annual maximum and minimum temperature will increase by 1.2 °C and 1.3 °C by the year 2050 and by 2.4 °C and 2.6 °C at the end of 2100 relative to the baseline period of 1981-2010. Rainfall is projected to increase by 2.6% by 2050 and by 6.9% increase by 2100. While temperatures are projected to increase in the Tasmanian potato growing regions, the modelled duration for which the potato crop may be exposed to temperatures outside its optimum range is negligible e.g. the number of days when daily mean temperature is within a growth limiting high temperature (Ht) range (≥24 °C but < 34 °C) increases from less than 1 day during the baseline period to approximately 5 days (5.1 days at Cressy, 2 at Forthside and 7 days at Scottsdale) by 2100.

Simulation results using ‘Russet Burbank’ show no major changes in tuber yield throughout the 21st century which may reflect the lack of change in temperatures which would impact potato productivity. This lack of change in tuber yield of ‘Russet Burbank’ may also reflect tuber yield for the cultivar has reached its potential yield and that climatic conditions and management events such as irrigation and fertilisation are near optimal for potato production. A simulated steady increase in the rate of growing day degrees (°Cd, GDD) accumulation forecast a potential shortening of duration to maturity by 10-15 days by 2085 relative to the baseline period, 1981-2010. Irrigation requirements were projected to decrease slightly by end of the 21st century.

Shorter growth cycles and reduced irrigation requirements may translate into efficient gains for water and pesticide use especially if the crop can be planted earlier (planting date was fixed in simulations). The simulations however do not take into account other significant information which might influence potato production in Tasmania in future such as pests and diseases. In the important NW potato growing region of Tasmania as represented by Forthside, end of the 21st century rainfall is expected to increase up to 20% in winter and spring and decrease by 10-20% during summer and autumn (Corney et al. 2010). These changes in rainfall are expected to generate more intense downpours along with longer dry periods.

While irrigation may be applied in dry periods, the management of waterlogging in potatoes is more problematic as the crop is sensitive to excess water (Van Oort et al. 2012; Saue & Kadaja 2014). In areas where increased rainfall is predicted, leaching of nutrients, especially nitrogen, incidence of diseases such as late blight (*Phytophthora infestans*) pink rot (*Phytophthora erythroseptica*) and black leg (*Pectobacterium carotovorum*) can be aggravated (Boland et al. 2004; Haverkort & Verhagen 2008; Pavek 2014).

Climate projections for the two potato growing sites in Kenya (Bomet and Kabete) indicate more dramatic changes in climate compared to those projected for Tasmanian potato growing sites. Annual maximum and minimum temperature is projected to increase by 1.5 °C and 2.0 °C by 2050 and by 3.2 °C and 3.8 °C by 2100 relative to the baseline period of 1961-1990. A 22.3% reduction of annual rainfall is projected by 2050 and 13.2% reduction by 2100. Inter-annual and inter-seasonal rainfall variability is marked, with no clear trend throughout the 21st century. Kabete will experience a significantly greater number of high temperature (Ht) day (⩾24 °C but < 34 °C) as the century progresses compared to Bomet. However, neither Kabete nor Bomet will experience days with very high temperatures (VHt) of above < 34 °C. With APSIM-Potato, temperature stress factor (ft) values rise from zero to a maximum value of 1.0 at daily mean temperatures of between 12 and 24 °C. Above 24 °C, the ft values declines to zero at 34 °C based on daily average temperatures of 2 °C (Tbase).

In Kabete the tuber yield (mean value for Short and Long Rains) projected for 'Shangi' increased by 11.3% by mid-century and 15.2% by 2100 relative to the baseline period, 1961-1990. In Bomet, the mean tuber yield for the two rainy seasons also increased by 28.8% and 30.7% by 2050 and 2100 respectively. These positive impacts of climate change do not agree with many previous studies (e.g. Hijmans 2003) but the modelling carried out in these studies may not have taken into account interactions between different climatic variables. Simulation results presented in Chapter 5 illustrate that as temperature and atmospheric CO_2 increases, the interaction between these factors and rainfall determines the growth and development and tuber yield under rain-fed conditions in Kenya. If the temperatures are within the optimum range or potato plants are exposed to short-term period of high temperature, tuber yields are driven by rainfall amount and distribution. Poor rainfall distribution within the year had a strong effect and low yields were obtained even if total annual rainfall was high.

The comparison between the two sites in Kenya is interesting. As temperatures at Bomet are likely to be within the optimal range for potatoes, tuber yield will most likely be driven by rainfall amount, and more importantly, rainfall distribution. In Kabete, where temperatures are predicted to be intermittently above the optimal range later in the century, temperature and rainfall were both key and potentially at times, depending on the distribution of rainfall, opposing drivers in determining potato tuber yield. The benefits of increasing CO_2 concentrations may have counteracted the more negative impacts of elevated temperatures at Kabete. At Kabete and to a lesser extent at Bomet simulated potato yields become more variable as the century progresses suggesting that trade-offs between the impacts of climate variable changes.

This study simulation appeared to favour the continued production of potatoes in the Kenyan highlands where they are conventionally cultivated as at Bomet; other sites in the highlands such as Kabete may become marginal for potato growing. In medium to low altitude areas in Kenya, high temperatures will become a major constraint. There is however a growing interest to introduce potatoes in the non-traditional lower altitude areas of Kenya due to the increasing demand for the potato driven mainly by its earliness compared to maize, the country's staple food. This work highlights that this could only be done using new thermo-tolerant clones.

The International Potato Center (CIP) has developed thermo-tolerant clones. The clones belong to either the Late blight heat resistant (LBHT) population or the Lowland sub-tropics virus resistant (LTVR) population, and some of the clones have been tested and adopted in a few countries such as China, Tajikistan, Uzbekistan and Kazakhstan (Carli et al. 2014; Gastelo et al. 2014). Several thermo-tolerant cultivars have been extensively evaluated in Kenya but only 'Unica' which was officially registered in 2016 is available for farmers. Based on the good tuber yield reported in this thesis, 'Unica' a thermo-tolerant cultivar from the LVTR population has potential to produce high tuber yields under heat stress conditions. Importantly, adoption of clones from the LTVR population will be beneficial given that viruses are a major tuber yield-reducing factor in Kenya especially in the low altitude areas (Gildemacher et al. 2009; John et al. 2013; Were et al. 2013). According to Gildemacher et al. (2009), over 90% of the seed tubers sold in the informal market in Kenya are virus infected. Aphids are found even in high altitude areas above 2500 AMSL (Were et al. 2013) hence the need for virus resistance genotypes.

The farmer selected and most popular cultivar 'Shangi' unexpectedly gave the lowest tuber yields among the three genotypes investigated in this study. Intriguing questions are raised relating to farmer perception of 'Shangi' as a good variety because it does appear to be based on yield. According to potato farmers (personal communication to farmers from Nakuru and Nyandarua Counties, the two major areas where 'Shangi' is the preferred cultivar), excellent cooking and processing attributes for fresh and processing markets, short maturity period and very short dormancy period are the main reasons why they prefer 'Shangi' to other registered cultivars. Early tuberization in Kenya is considered an important attribute as the crop can be harvested as 'early' crop for family use and its short dormancy will ensure availability of sprouted tubers for immediate subsequent planting. These results show that farmers should be given a wide selection of cultivars that meets their preference.

Although ‘Unica’ is seen as a promising cultivar for the processing market with potential for high tuber yield and longer storability due to longer dormancy, it is expected to face competition from ‘Shangi’ as long as quality seed tubers for ‘Shangi’ are available. The popularity of ‘Shangi’ is a caution against using tuber yield alone to investigate the impact of climate change and the need to understand the potato production system as it is relevant to the Kenyan farmer.

Conclusions

The model’s accurate prediction of plant phenology and TDM provided a sound basis to investigate the potential effect of climate change on potato productivity with confidence. Consequently, the re-parameterized APSIM-potato model was used to quantify the potential impact of future climate scenarios on potato productivity in the two contrasting environments of Tasmania and Kenya. From the discussions section of chapter 3 to 5 and the discussions above, the following conclusions are drawn:

1. APSIM-potato model demonstrated capacity to simulate tuber dry matter yield and nitrogen uptake under Tasmanian conditions, and this justifies its use in potato modelling studies.
2. Under suboptimal water stress conditions in Kenya, the APSIM-potato model realistically reproduced observed TDM though to a lower accuracy compared with the cultivars response modelled in Tasmania. Nevertheless, the simulation was considered good enough to provide confidence for use of the model to simulate production studies for Kenyan cultivars.
3. This simulation presented in this study provides a foundational database for other researchers and as more data on field performance of potato in Tasmania are made

available, the ability of APSIM-potato to simulate aboveground biomass and LAI can be improved for both ‘Russet Burbank’ and ‘Moonlight’.

4. Similarly, further experiments are required to improve cultivar specific input parameters such as phenology, leaf area and leaf duration and other functions that needs further refinement to improve model ability to simulate plant organs beside the tuber for the cultivars grown in Kenya.
5. Future studies could focus on incorporating pest induced yield losses into the model as this is a critical issue in the tropical highlands and not currently addressed in APSIM-potato.
6. As part of refining the model, more testing of its performance is recommended with additional locations, years, and management options.
7. To improve simulation under suboptimal tropical conditions, drought induced branch mortality and drought induced senescence accelerator, the two crop parameters, which are currently constant, should be adjusted in order for the model to capture accelerated senescence, as drought is a common occurrence under tropical rain-fed conditions.
8. For the generation of future climatic data, refinement of the projected data and bias-adjustment is recommend for Kenya as there were large disagreements among the projected datasets generated by the different GCMs used in the study to generate future climate data for the two study sites.
9. More studies on adaptation of pest resistance and thermo-tolerant cultivars is also recommended.

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Appendices

The following are the supplementary data associated with this Thesis.

Appendix 1 Photos showing field data collection activities both in Tasmania and in Kenya.

Lower Barrington 1: Sequential harvesting at the on-farm plot and harvested plants separated into leaves, stems and tubers. (Photo taken on 13 December 2012 and the field was planted on 16 October 2012).

TVRF: Measuring LAI with SunScan (SS1, AT Delta-T Devices Ltd, UK) at the on-farm plot. (Photo taken on 16 December 2012 and the field was planted on 20 October 2012).

Sassafras: Final harvest-Sorting, grading, weighing and taking samples of tubers for oven drying. (Photo taken on 16 March 2013 and potatoes were planted on 15 October 2012).

Lower Barrington 2: Freshly-excavated soil pit up to 1.2 m used for collection of soil cores for characterization of soil profile. (Photo taken on 4 April 2013 after final harvesting). Soil profiling was done at all the trial sites both in Tasmania and Kenya.

SR2013 trial site, Kabete Farm: Field crop at vegetative stage. (Photo taken on 23 December 2013 and the field was planted on 4 November 2013).

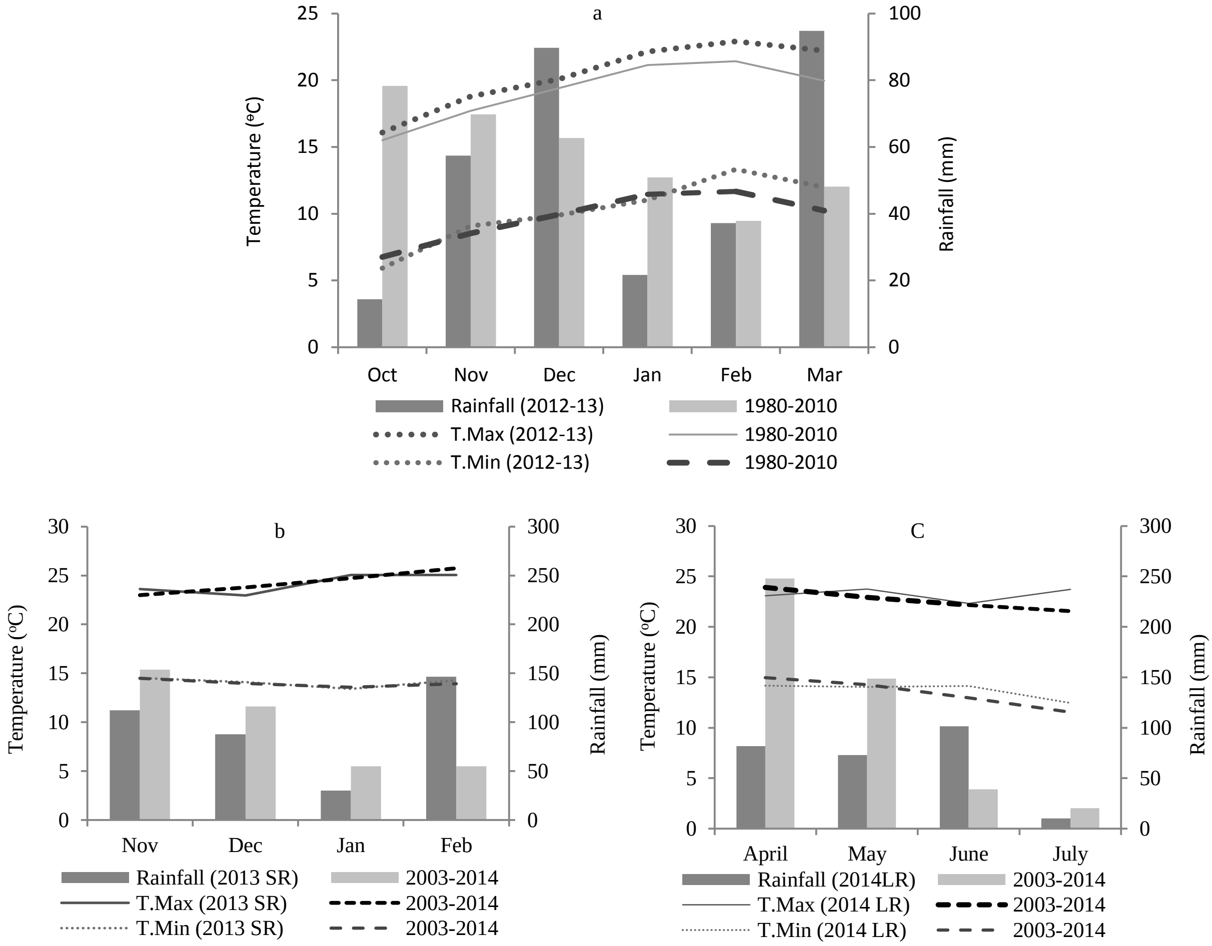
SR2013 trial site, Kabete Farm: Final harvesting- sorting, grading, weighing and taking samples of tubers for oven drying. (Photo taken on 24 February 2014 and potatoes were planted on 4 November 2013).

LR2014 trial site, Kabete Farm: Field crop at tuber bulking/full flowering stage. (Photo taken on 14 May 2014 and the field was planted on 3 April 2014).

LR2014 trial site, Kabete Farm: Sequential harvesting and harvested plants separated into leaves, stems and tubers, (Photo taken on 5 June 2014 and the field was planted on 3 April 2014).

Appendix 2 Area of Land under Potato, Production in Million Tons (Mt) and Average Yield in t ha^{-1} for the Period from 2003 to 2013 in Australia, Tasmania and in Kenya. Source (ABS 2014[a], FAO 2015[b]).

	Australia [a & b]			**Tasmania** [a&b]			**Kenya** [b]		
Year	Ha	Mt	t ha^{-1}	Ha	Mt	tha^{-1}	Ha	Mt	t ha^{-1}
2003	34,542	1.2	34.7	6,500	320,300	49.3	123,711	1.2	9.7
2004	35,832	1.3	36.3	6,800	327,600	48.2	130,952	1.1	8.4
2005	37,780	1.3	34.4	6,700	320,800	47.9	130,000	2.6	20
2006	33,870	1.2	35.4	6,300	288,600	45.8	120,000	2.4	20
2007	33,755	1.2	35.6	6,600	301,700	45.7	110,000	2.2	20
2008	38,189	1.4	36.7	6,000	311,200	51.9	134,884	2.9	21.5
2009	33,177	1.2	36.2	5,700	278,400	48.8	120,419	2.3	19.1
2010	37,005	1.3	35.1	6,600	332,700	50.4	120,536	2.7	22.4
2011	31,348	1.1	35.1	6,000	251,800	42.0	125,000	2.4	19.2
2012	33,978	1.3	38.3	-	-	-	142,857	2.9	20.3
2013	33,731	1.3	38.5	6,348	350,470	55.2	152,778	2.2	14.4



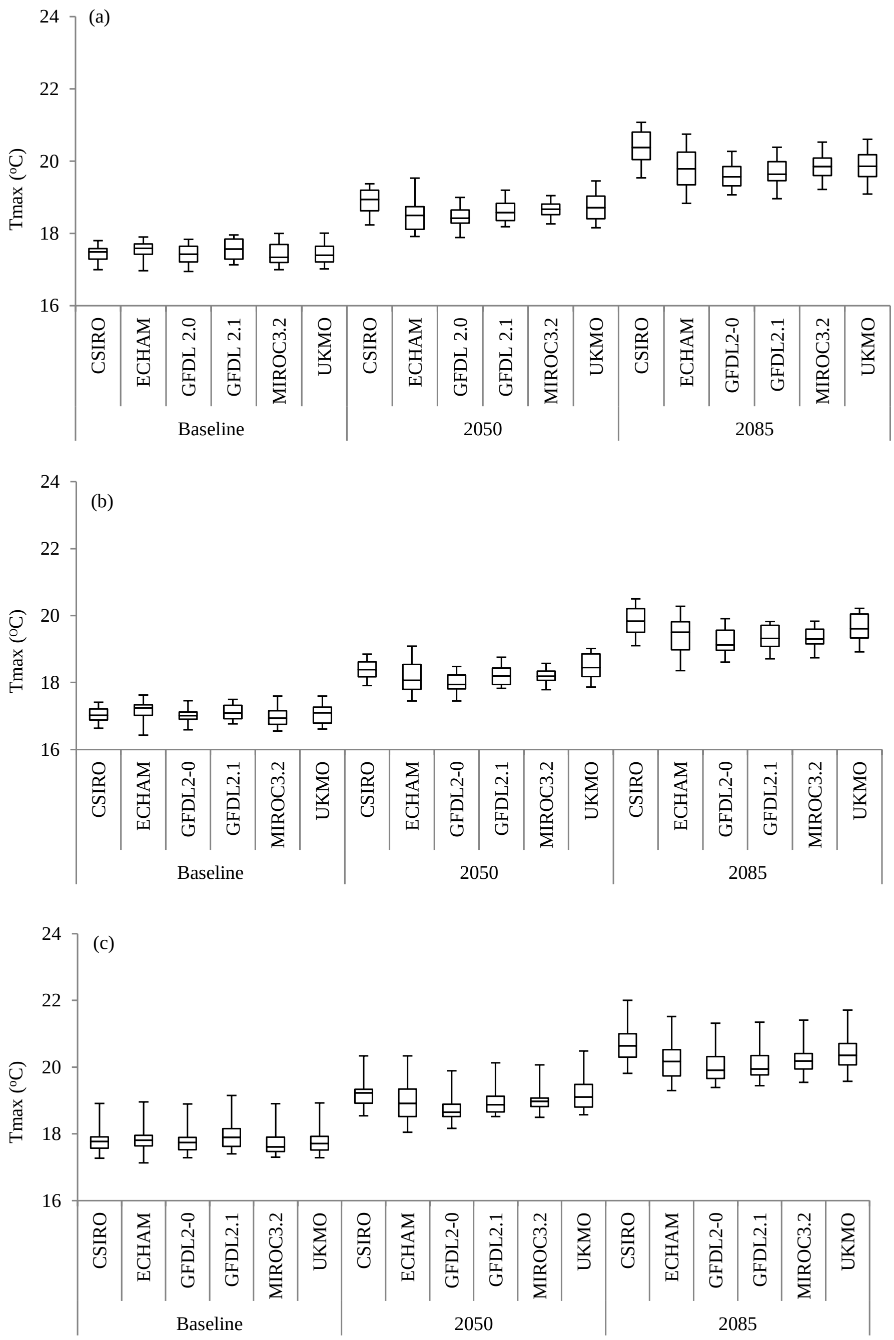
Appendix 3 Monthly average maximum and minimum temperature for Tasmania (pooled averages for the four trial sites) during the 2012-13 growing season and for the period 1980-2010 (a) and for Kabete, Kenya during the SR2013 (b) and LR2014 (c) and for the period Jan 2003 - Sept. In Tasmania, potatoes are planted between mid-spring and early summer (Sept. – Dec.) and in Kenya potatoes are planted during the SR (March-April- May) and LR (Oct.-Nov-Dec).

Appendix 4 Differences between potato production system in Tasmania and Kenya.

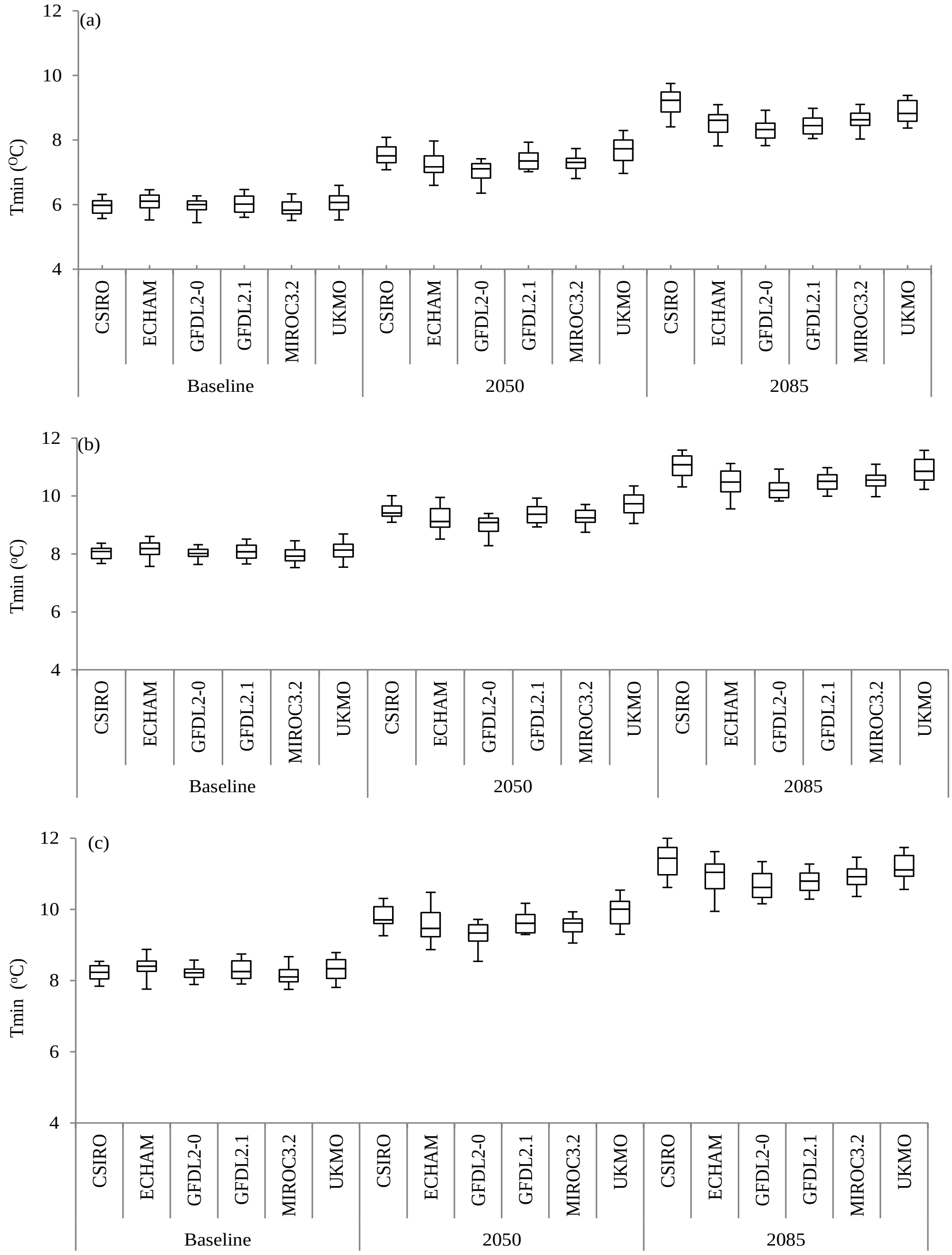
	Tasmania	**Kenya**
Geographical loc.	High latitude (Southern)	Low latitude
Climatic conditions	Maritine	Tropical
Photoperiodism	long day conditions	short day conditions
Seed production and distribution system	Efficient	Inefficient
Seed tubers	Large tubers (over 280 g) are usually cut into pieces called sets which are planted. Each set usually weights about 50 g and should have at a least one eye and the buds in the eyes should be more than 2 mm long	Whole tubers are used and the tubers size ranges between 28-45 mm diameter for size 1 and 46-55 mm for size 2
Farmers knowledge and skills	High	Low for majority of farmers
Crop protection	Optimal pest and disease management	Majority of the smallholder farmer's use suboptimal quantities of pesticides resulting in high pest ad disease incidence
Pests and diseases of economic importance	Common scab (*Streptomyces scabiei*), powdery scab (*Spongospora subterranea*) and black scurf (*Rhizoctonia solani*) Root knot nematode	PTM (*Phthorimaea operculella*) and leaf miner, late blight, bacterial wilt, Virus (PLRV, PVY, PVX, PVS) and black scurf (*Rhizoctonia solani*)
Plant biosecurity	Potato Industry Biosecurity Plan first released in 2007 outlines the high priority pests (HPP) threats	Weak biosecurity protocols with high chance of contaminated seed being sold and grown in the country
Farm operations	Precision agriculture with fully mechanized farm operations	Except for land preparation,farm operations are done manually and in some parts of the country where land is undulating, land preparation is done manually
Inputs application	Optimal input application	Suboptimal characterized by recycling of seed and low rates of fertilizers. Often farmers use small tubers as seed after selling the marketable tubers
Supply chain	Processing potatoes (~80% of the total produce) supplied to on growing contracts to the two companies: Simplot and McCain companies. Seed potatoes are also contracted to the two companies.	Few contractual arrangements and limited access to credit and markets resulting in seasonal price fluctuations
Land size under potato		Ranges between 2-15 acres per season with few large scale farms (public and private) cultivating about 20 acres per season
Infrastructure	Good infrastructure (rural access, marketing ,storage and packaging facilities, processing plants)	Poor infrastructure (poor rural access, limited marketing and storage facilities, processing plants)
Industry data	Adequate and reliable potato and weather data	Inadequate and inconsistent data on potato and unreliable weather data

Appendix 5 The list of parameters for ‘Moonlight’ and the Kenyan cultivars that were adjusted relative cultivar Russet Burbank (the base cultivar).

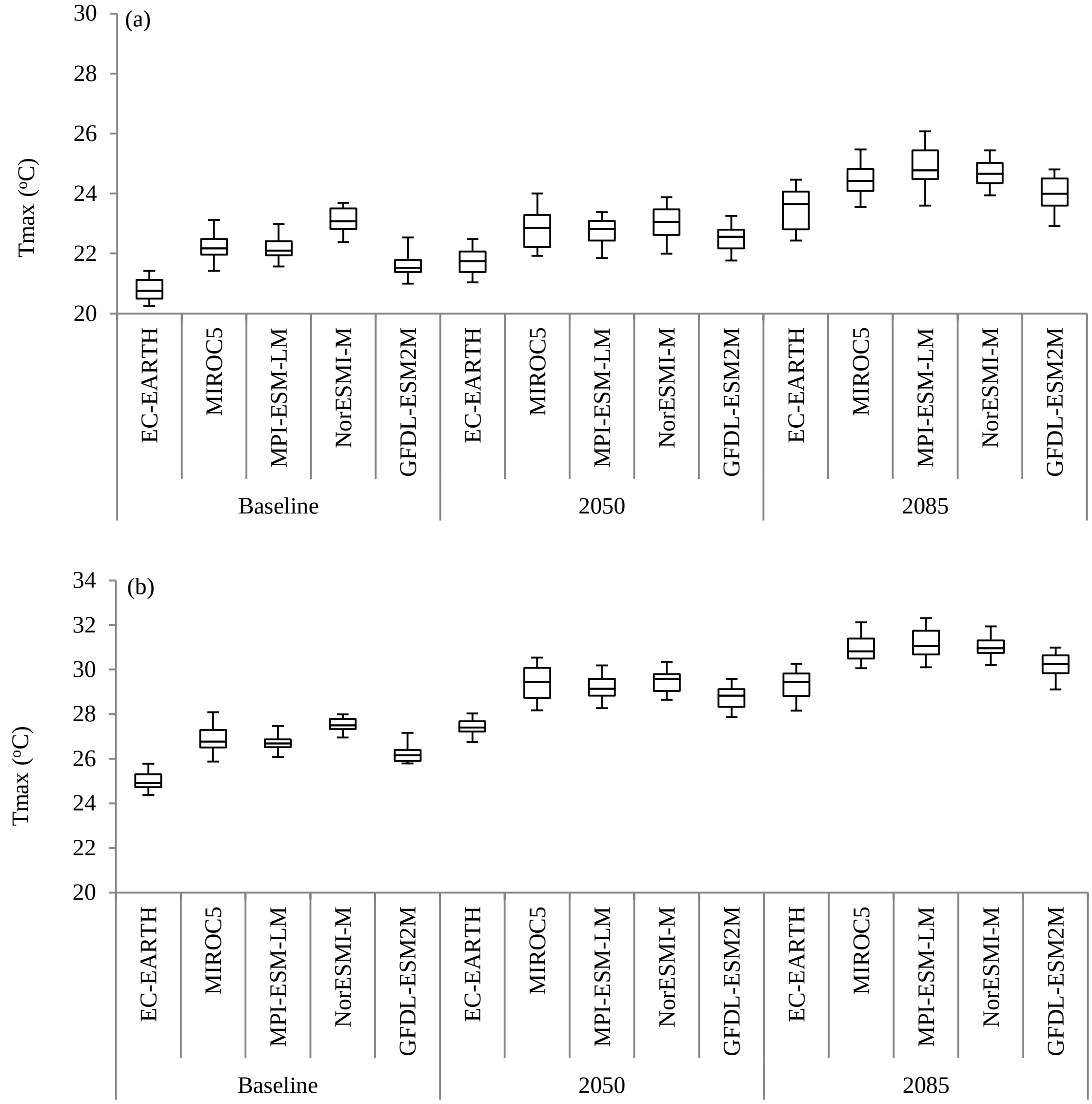
	Crop Specific Parameter	**Units**	**‘Shangi’**		**‘Unica’**		**CIP 300046.22**		**‘Moonlight’**		**‘Russet Burbank’**	
1	Structure.MainStemFinalNodeNumber	#	18		19		17		28		34	
2	Phenology.Vegetative.Target	day degrees	450		450		450		As for ‘Russet Burbank’		300	
3	Structure.BranchingRate.Potential_Branching_Rate		X	**Y**	X	**Y**	**X**	**Y**	**X**	Y	**X**	**Y**
			0	0	0	0	0	0	0	0	0	0
			5	1	7	1	7	0	7	0	7	0
			8	1	8	1	8	1	8	1	8	0.5
			9	0	9	0	9	0	9	0	13	0.5
											14	0
											34	0
4	Leaf.MaxArea	m^2m^{-2}	X	**Y**	**X**	**Y**	**X**	**Y**	**X**	Y	**X**	**Y**
			0	2000	0	2000	0	2000	0	2000	0	2000
			0.5	25000	0.5	18000	0.5	18000	0.15	18000	0.15	18000
			0.7	30000	0.7	30000	0.7	30000	0.3	20000	0.3	27000
			0.9	20000	0.9	25000	0.9	25000	0.44	10000	0.44	15000
									0.59	5000	0.59	6000
									0.73	1000	0.73	1500
5	Leaf.LagDuration	day degrees	**X**	**Y**	**X**	**Y**	**X**	**Y**	**X**	**Y**	**X**	**Y**
			0	300	0	350	0	350	0	400	0	350
			0.15	300	0.15	350	0.15	350	0.15	400	0.15	350
			0.3	300	0.3	350	0.3	350	0.3	400	0.3	350
			0.4	300	0.4	300	0.4	300	0.44	400	0.44	350
			0.73	200	0.73	300	0.73	300	0.73	400	0.73	350
			1	100	1	100	1	100	1	20	1	20
6	Tuber.DMDemandFunction.PotentialGrowthIncrement		**X**	**Y**	X	Y	X	Y	**X**	Y	**X**	**Y**
			4	0.017	4	0.017	4	0.017	As for ‘Russet Burbank’		4	0.01
			4.04	0.017	4.04	0.017	4.04	0.017			4.04	0.017
			4.5	0.03	4.5	0.03	4.5	0.03			4.32	0.06
			4.52	0.06	4.52	0.06	4.52	0.06			4.52	0.06
			5.5	0.06	5.5	0.06	5.5	0.06			4.95	0.018
			6.54	0	6.54	0	6.54	0			6.54	0



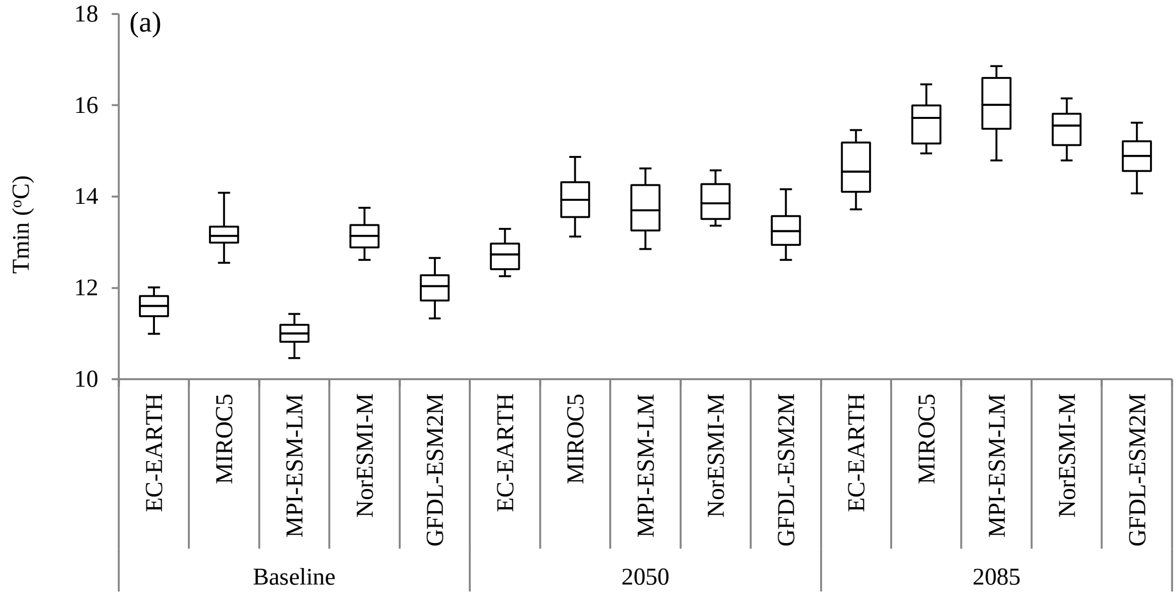
Appendix 6 Projected maximum temperature (°C) per GCM for three 30-year time slice, baseline period (1981-2010), 2050 and 2085 under A2 future climate scenario for the three potato growing sites, (a) Cressy, (b) Forthside, and (c) Scottsdale, Tasmania, Australia. The boxplot shows the 25, 50 and 75 percentile. The whiskers show 5% and 95% percentile.

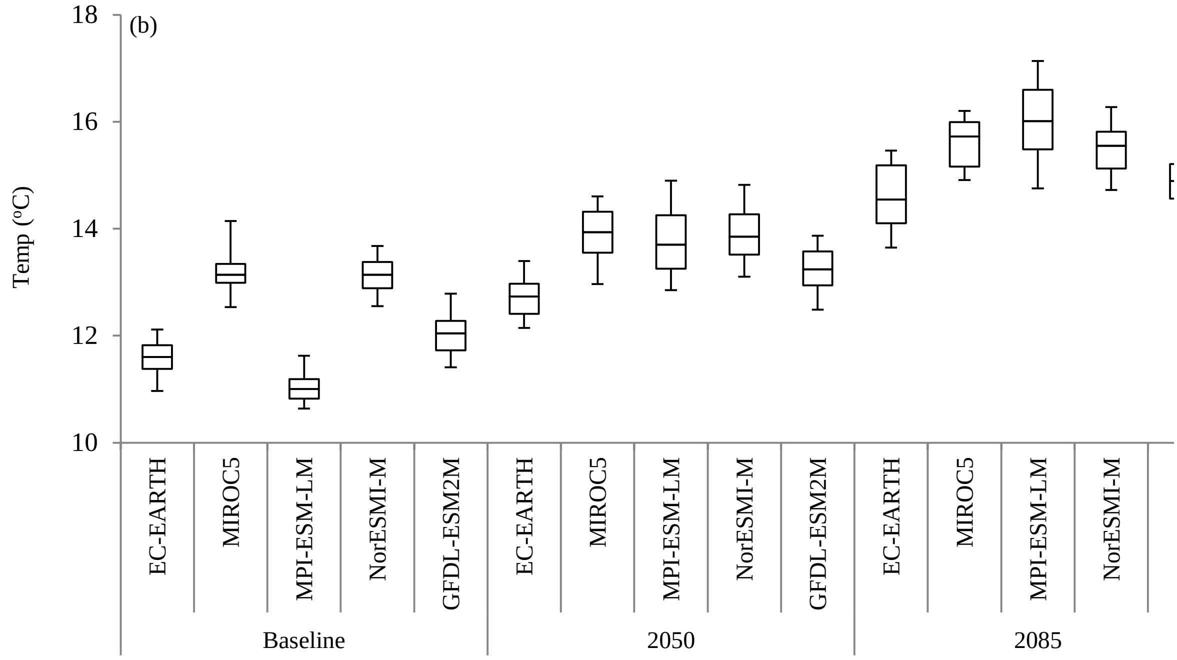


Appendix 7 Projected minimum temperature (°C) per GCM for three 30-year time slice, baseline period (1981-2010), 2050 and 2085 under A2 future climate scenario for the three potato growing sites, (a) Cressy, (b) Forthside, and (c) Scottsdale, Tasmania, Australia. The boxplot shows the 25, 50 and 75 percentile. The whiskers show 5% and 95% percentile.



Appendix 8 Projected maximum temperature (°C) per GCM for the three 30-year time slice, baseline period (1961-1990), 2050 and 2085 under RCP8.5 for (a) Bomet and, (b) Kabete, Kenya. The boxplot shows the 25, 50 and 75 percentile. The whiskers show 5% and 95% percentile.





Appendix 9 Projected minimum temperature (°C) per GCM for the three 30-year time slice, baseline period (1961-1990), 2050 and 2085 under RCP8.5 for (a) Bomet and (b) Kabete, Kenya. The boxplot shows the 25, 50 and 75 percentile. The whiskers show 5% and 95% percentile.

Appendix 10 Magazine Article:Predicting potato production in Tasmania and Kenya, article in Potatoes Australia Magazine, February/March 2015 Issue.

Predicting potato production in Tasmania and Kenya

VARIABILITY IN TEMPERATURE, RAINFALL AND OTHER ENVIRONMENTAL FACTORS ARE EXPECTED TO HAVE AN EFFECT ON THE YIELD OF POTATO CROPS, WITH THE GREATEST IMPACT IN LOW LATITUDE COUNTRIES. IN LIGHT OF THIS, A NEW POTATO MODEL WAS RECENTLY PUT TO THE TEST IN TASMANIA AND KENYA TO HELP PREDICT FUTURE POTATO PRODUCTION IN BOTH OF THESE COUNTRIES.

Harvested potatoes in Tasmania at Mark Clement's farm.

Given that the potato is consumed by over a billion people on a daily basis, it is imperative for industry to ensure that production levels remain at their highest despite the many environmental challenges that lie ahead.

Tasmania and Kenya formed the focus of a recent research project that aimed to predict how future environmental events could have an impact on potato production in these two countries. In Tasmania, potato represents 70 per cent of the vegetable industry's total value and nine per cent of the state's total agricultural value. It is also the second most important food crop in Kenya.

It is most likely that a modest increase in temperature will benefit potato production in high latitude countries, while it is expected to have an adverse effect on potato yields and potato growth and development in low latitude countries such as Kenya. An increase in temperature may also attract a higher incidence and increase the severity of potato pests and diseases in both Kenya and Tasmania.

Essentially, a potato crop demands a mean temperature of 18-20°C and 500-700mm of water to produce optimum yields. However, a reduction in the total annual rainfall is predicted in north-west Tasmania, where the majority of the state's potatoes are grown. The mean annual temperature is also expected to increase by about 2.9°C in 2100.

On the other side of the world in Africa, the temperature is expected to increase by more than 2°C in the same timeframe. The high-rainfall events are also projected to increase, with wetter rainy seasons, fewer droughts and a higher number of extreme wet events.

Project approach

Developed in the 1990s in Australia, the Agricultural Production System Simulator (APSIM) model simulates the biophysical process in farming systems. Given this, researchers enlisted the help of a new potato model to more accurately predict the effects of nitrogen fertiliser levels, sowing dates, plant density and irrigation in potato crops in Tasmania and Kenya.

A watchdog mini weather station was on each trial site in Tasmania.

The APSIM-potato is a new crop module that was incorporated into the APSIM Plant.net Framework in 2011. It predicts yield, nitrogen uptake and water use efficiency of potatoes on a daily basis in response to inputs of daily weather data, soil characteristics, crop parameters and management events.

This is the first time the APSIM-potato model has been tested and compared under either Tasmanian or Kenyan conditions. Researchers conducted field trials using a range of cultivars in both countries to calibrate and evaluate the model, and determine if it can realistically predict potato phenology and yield under the local conditions.

Field experiments in Tasmania

In Tasmania, plots were established within potato fields in the 2012/13 crop season and all the management events were carried out by the grower. There were four different on-farm plots and each plot measured 21 metres long by 10 rows wide. At each site, certified seed sets of two commercial potato varieties (Russet Burbank and Moonlight) were planted.

Data was collected on a weekly basis starting at 50 per cent emergence. For each sequential harvesting, two adjacent plants were harvested from six locations within the on-farm plot, giving a total of 12 plants per plot. Growth and development parameters were recorded immediately after harvest, before the plants were separated into leaves, stems and tubers. The roots were discarded.

Fresh weights of each of the 12 separated plants were recorded before a sub-sample was taken for nitrogen analysis. The dry weight of each component was determined by oven drying the sub-samples for nitrogen analysis. Where samples were too bulky, they were sub-sampled before drying. Tubers were washed, sub-sampled in regard to tuber size distribution, cut longitudinally and diced before drying.

Soil samples were also collected after harvesting and used to determine soil hydraulic properties. At all the sites, daily weather data was recorded using on-site data loggers.

Field experiments in Kenya

In Kenya, experiments were conducted during the 2013 "short rains" and 2014 "long rains" season at The University of Nairobi, Kabete farm. The experimental design for the 2013 short rains (April to June) was a split plot, with two water levels (supplementary irrigation and rain-fed) as the main plot and three genotypes as the sub-plot. A randomised complete block design was used in the 2014 "long rains" (March to July) experiment with three nitrogen levels (22.5kg/ha, 63kg/ha and 103kg/ha) and four replicates.

In both experiments, certified sprouted tubers or mini-tubers of three genotypes were used: Shangi (a farmer's selection variety) and two thermotolerant advanced International Potato Centre clones from lowland tropics virus resistance (LTVR). Tubers were planted 10cm deep, 0.75m by 0.3m, and two outer rows were established as border rows. Each sub-plot included six rows of 12 plants.

Final harvest at TIA Forthside farm in Tasmania.

The results are in

This was the first time the APSIM-potato model was used in Tasmanian potato crops, which have well defined and fairly reliable growing conditions. However, the production system in Kenya is quite different in terms of climate and genotypes and, given the variable and harsh conditions at the trial site in Kenya, calibration of the model is likely to be challenging.

In general, the model better predicted the date for emergence and the vegetative stage than the later growth stages for Russet Burbank at both the Sassafras and Lower Barrington sites in Tasmania. For the six different phenological growth stages, there was a difference between predicted and observed data, ranging between 4-27 days and 2-35 days for Russet Burbank at the Sassafras and Lower Barrington trial sites respectively. However, the model does require some adjustment to improve its performance on-site.

In addition to understanding the influence of changing weather conditions on potato production, model outputs about planting dates, irrigation strategies, nitrogen fertilisation and other aspects will be useful for both industry and research in the future.

This project was funded by AusAID and the Tasmanian Institute of Agriculture (TIA) with additional support from the International Potato Centre (CIP) in Nairobi. The researchers also thank Simplot Australia, participating potato growers and Hamish Brown for technical advice on the APSIM-potato model.

Potato is the second most important food crop in Kenya.